THE ENVIRONMENTAL EFFECTS OF UNDERWATER EXPLOSIONS WITH METHODS TO MITIGATE IMPACTS

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August 1997

ACKNOWLEDGEMENTS

Preparation of this manual and the original research that made parts of this possible were funded by the LEGACY Program and by the St. Louis District, U.S. Army Corps of Engineers.

We owe a special note of thanks to Dr. David Schaeffer (University of Illinois) who was extremely helpful in the development of study designs, statistical analysis, and publication of reports. Dr. Schaeffer participated in much of the original research effort.

We appreciate the assistance of the St. Louis District Library, Arthur Taylor (Director), Sandra Argabright, Phyllis Thomas and Hazel Schnatzmeyer. They were given the task of obtaining hundreds of reports and publications, most very obscure.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **AUG 1997**	2. REPORT TYPE	3. DATES COVERED **00-00-1997 to 00-00-1997**
4. TITLE AND SUBTITLE **The Environmental Effects of Underwater Explosions with Methods to Mitigate Impacts**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Corps of Engineers,St. Louis District,1222 Spruce Street,St. Louis,MO,63103-2833**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**99**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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INTRODUCTION

In- or near-water use of explosives (i.e., construction or demolition projects; ordinance testing and disposal; as well as, harbor maintenance projects; and use of explosives during training exercises) can adversely affect significant aquatic ecosystems or organisms. Many of the potential environmental problems associated with use of explosives in aquatic environments are unique to the Department of Defense (i.e. ordinance testing & training). The literature on blasting effects is obscure and would be difficult to gather in a timely fashion by environmental planners and resource managers attempting to practice good stewardship of Department of Defense managed water resources. The goal of this manual is to provide resource planners/managers with information, which allow quick assessments of potential problems associated with underwater explosive use.

This handbook summarizes available literature (e.g., published, state and Federal reports) on the environmental effects of underwater explosions and provides information on the potential use of mitigative strategies to reduce impacts to significant biological systems and species. Chapter 1 outlines natural resource agency concerns and regulatory authority concerning explosive use. Chapter 2 provides information concerning explosives, the physics of explosions, and how explosives react in various media. It is not the intent of this chapter to provide an exhaustive review of the physics of explosions. We have attempted to provide enough information to make the chapters on environmental effects more understandable. The effects of underwater explosions on aquatic plants (Chapter 3), aquatic invertebrates (Chapter 4), fish (Chapter 5), amphibians and reptiles (Chapter 6), aquatic mammals (Chapter 7) are reviewed. Chapter 8 provides information on mitigation techniques to reduce adverse environmental effects of underwater explosions.

A user-friendly computer program with users manual for planners/managers which allows quick assessments of potential environmental problems is also being developed under this LEGACY project. The computer program will provide impact analysis (kill radius for fish) based on the amount, depth, and use (open-water versus confined blast) of the explosive being detonated.

There is a considerable amount of research on the environmental effects of underwater explosions still in progress by the authors. In addition, the authors have established a Natural Resources Working Group within the International Society of Explosives Engineers to tackle some of the outstanding questions in this field, such as standardization of pressure transducer calibration, standardization of pressure measurement and reporting, standardization of experimental designs for mortality assessment, and identification of data gaps and prioritization of data collection needs. As such, this manual should be considered a working document. If you have any comments or questions, please feel free to contact the authors. Dr. Thomas Keevin is an Aquatic Ecologist and Dr. Gregory Hempen is a Geophysical Engineer.

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CHAPTER 1
UNDERWATER EXPLOSIVES USE:
NATURAL RESOURCE AGENCY
CONCERNS AND REGULATORY AUTHORITY

RATIONAL FOR NATURAL RESOURCE AGENCY CONCERNS

Population growth and economic development have resulted in frequent changes in our hometown landscapes and their waterways due to housing developments, shopping malls, industrial development, and roadways. Population growth and development have resulted in a loss of aquatic habitat and a general decline in water quality, both important factors in sustaining aquatic species. For example, since 1850, 67% of the fish species from the Illinois River and 44% from the Maumee River have become less abundant or have disappeared (Kerr et al. 1985). These are just two examples of aquatic degradation and loss of fish species that are occurring throughout the United States (Warren and Burr 1994). The list of aquatic invertebrates and vertebrates that are federally protected or under consideration for protection (candidates) continues to increase and totals more than l,O00 taxa (Williams and Neves 1992). In fact, 27 species and 13 subspecies of fish have become extinct in North America during the past 100 years (Miller et al. 1989).

Marine resources are suffering similar assaults on their biological integrity as described for freshwater ecosystems. Overharvesting, toxic and nutrient pollution, costal development, and increasing ultraviolet radiation threaten marine species (Upton 1992).

Habitat degradation has jeopardized the continued existence of many species. Both federal and state laws afford protection to numerous aquatic organisms. The following listing makes it clear that it is difficult to utilize explosives underwater, in a major river basin or in the marine environment, without the potential for adversely impacting a federally threatened or endangered species or a species of special concern to federal and state natural resource agencies.

<u>Aquatic Mammals</u>. The U.S. Fish and Wildlife Service (1993) lists 15 species of marine mammals that occur in U.S. coastal waters or near our trust territories as threatened and endangered, including such species as the West Indian manatee (Florida manatee), Southern sea otter, Steller sea lion, 3 species of seals, and eight species of whales.

<u>Reptiles</u>. Of special concern for the blaster, in U.S. coastal marine environments there are 6 sea turtle species listed as either threatened or endangered (U.S. Fish and Wildlife Service 1993).

<u>Fish</u>. Williams et al. (1989) considered 364 fish species and subspecies in North America that warrant protection because of their rarity. Their list consists of 147 fishes classified as special concern, 114 as threatened, and 103 as endangered. Twenty-two of the fishes occur in Canada, 254 in the United States, and 123 in Mexico. Some occur along international borders and, therefore, inhabit two countries.

<u>Freshwater mussels</u>. Of the 297 native freshwater mussels of the United States and Canada, Williams et al. (1993) considered 213 taxa (71.7%) as endangered, threatened, or of special concern; only 70 (23.6%) were considered as currently stable. Twenty-one taxa (7.1%) were listed as possibly extinct, 77 (26.0%) as endangered, 43 (14.5%) as threatened, 72 (24.2%) as of special concern, and 14 (4.7%) as undetermined.

Crayfish. Of the 338 crayfish of the United States, Taylor et al. (1996) considered 162 taxa (48%) as possibly extinct, endangered, threatened or of special concern. Of these, 2 (<1%) are possibly extinct, 65 (19.2%) are endangered, 45 (13.3%) are threatened, and 50 (14.8%) are of special concern. Taxa classified as currently stable total 176 (52%).

The above litany of extinctions and aquatic species classified as threatened, endangered or of special concern form the basis of natural resource agency concerns over aquatic resources. As population growth and economic development continues, there will be more and more habitat degraded and species placed in jeopardy. Underwater explosives use is often considered by natural resource agencies as another assault on the resources that the agency is mandated to protect.

Natural resource agencies are challenged with permitting, under various regulatory authorities, underwater explosive use while at the same time protecting aquatic resources. Deciding on whether or not to allow use of explosives requires striking a balance between development and aquatic resources protection. On a positive note, natural resource personnel are generally willing to work with and accommodate the blaster.

NATURAL RESOURCE AGENCY REGULATORY AUTHORITY

In the United States, there currently are no national guidelines or regulations concerning mitigation of explosive use impacts. Decisions are left to individual state agencies and regulatory authority may rest with more than one state agency. In Canada, National guidelines for the use of explosives in Canadian fisheries waters have been prepared by the Department of Fisheries and Oceans under the Fisheries Act (Wright In press).

Keevin (In press) reviewed state natural resource agency permit requirements for underwater explosive use within waters under their jurisdiction (Table 1.1). To determine current agency policies on the use of explosives, a questionnaire was sent to fish and wildlife agency directors in each state. Questions were developed to determine current state fish and wildlife agency policies concerning the use of explosives for legitimate purposes (i.e., military testing programs, demolition, construction) within waters under their jurisdiction. Questions targeted three areas of concern for fish and wildlife agencies: (1) what type permit, if any, was required; (2) what information did the agency provide to the applicant; and (3) what mitigative techniques were required of the applicant by a agency or recommended to protect aquatic 1ife from explosive pressures (Issue #3 is covered in Chapter 8).

1. Permit Requirements. Thirty three state natural resource agencies require permits to conduct underwater blasting. There is often more than one agency responsible for permitting within a given state, depending on the location of the blasting, (freshwater, marine, or wetland), or the type of project, (demolition or seismic exploration).

Most agencies require permits based on existing fish and wildlife codes, codes that are nonspecific to underwater blasting (i.e. fishing codes, stream protection acts, or wetland protection laws). For example, the Montana Department of Fish, Wildlife and Parks' permitting authority rests with the Stream Protection Act and The Natural Streambed and Land Preservation Act. However, many states permitting or review authority is based on fishing codes; since many codes specifically indicate that it is illegal to take fish with explosives. In some states taking fish with explosives is illegal by default, since explosives are not listed as an approved fishing method.

Two states, Oregon and Pennsylvania, have permit application forms specific to underwater explosive use and resource protection. The Oregon Department of Fish and Wildlife's In-Water Blasting Permit Application Form requires that the applicant provide detailed information on explosive type, amount, size and number of charges to be detonated, detonation delay information, and estimated start and completion data. The Oregon applicant is also required to provide information concerning project impacts and proposed mitigation measures including: fish and wildlife species which occur in the blast area and predicted effects of the blasting on these species, fish and wildlife habitat within the affected area and the predicted effects of blasting on these habitats, estimated distance of impacts and area affected, and measures the blaster (before and after construction) will use to prevent injury to fish and wildlife and their habitats including an analysis of their effectiveness under the environmental conditions at the project site.

The "Guidelines for the Use of Explosives in Canadian Fisheries Waters" require that the blaster prepare an environmental impact assessment of the project describing the potential adverse effects on the fish and marine mammal resources and their habitats in the project area. This document is submitted to the Department of Fisheries and Oceans regional/area authority. The blaster is also required to prepare a plan to mitigate adverse effects on fish and fish habitat identified in the environmental impact assessment. The blaster must complete a detailed application form, specific to underwater explosive use, for authorization to kill fish by means other than fishing. Detailed information is required on the type, weight and weight per delay of explosives, shot pattern, detonation depth, delay period (msec), and method of detonation. The environmental impact assessment and mitigation plan are required as part of the application submittal. Although these guidelines are draft they are currently in use by the Department of Fisheries and Oceans.

Seventeen state natural resource agencies responded that they do not require permits for the use of explosives in waters under their jurisdiction. However, these agencies may provide input to other agencies within their state and to federal agencies. Under the Fish and Wildlife Coordination Act, state natural resource agencies have the authority to review and comment on applications for U.S. Army Corps of Engineers' Section 404 (Clean Water Act) permits as a means of providing input to the decision making process. Federal explosive use projects (including any military related activities), projects requiring federal permits or receiving federal funding also fall under the jurisdiction of the National Environmental Policy Act (NEPA) and the Endangered Species Act. The NEPA requires Environmental Assessments of project impacts and possibly Environmental Impact Statements.

The Endangered Species Act requires a Biological Assessment of potential impacts to Federally threatened and endangered species and species Proposed for listing.

2. Information package on explosive-use provided to applicant by agencies. Only five states provide an information package to the blaster (Table 1.1). The majority of the information packages are related to use of explosives for seismic exploration. For example, the Mississippi Department of Natural Resources provides a booklet outlining rules and regulations governing geophysical and seismic exploration on state-owned lands. The Louisiana Department of Wildlife and Fisheries provides information outlining regulations governing explosive use for seismic exploration within the state. Both packages, which are not lengthy, provide information concerning requirements for observers, explosive charge size limits, minimum shot hole depths for a range of explosive sizes, and measures to mitigate impacts. The Canadian Department of Fisheries and Oceans provides the blaster with their "Guidelines for the Use of Explosives in Canadian Fisheries Waters," which explains environmental impact assessment and mitigation planning requirements and contains permit application forms.

Table 1.1 Summary of State Natural Resource Agency Responses

	AL	AK	AZ	AR	CA	CO	CT	DE	FL	GA
AGENCY PERMIT	Y	Y	N	N	Y	N	Y	Y	Y	N
AGENCY PROVIDES INFORMATION PACKG	N	Y	N	N	N	N	N	N	N	N
	HI	**ID**	**IL**	**IN**	**IA**	**KS**	**KY**	**LA**	**ME**	**MD**
AGENCY PERMIT	Y	N	Y	Y	N	N	N	Y	Y	Y
AGENCY PROVIDES INFORMATION PACKG	N	N	N	N	N	N	N	Y	N	N
	MA	**MI**	**MN**	**MS**	**MO**	**MT**	**NE**	**NV**	**NH**	**NJ**
AGENCY PERMIT	Y	Y	Y	Y	N	Y	Y	N	Y	Y
AGENCY PROVIDES INFORMATION PACKG	N	N	N	Y	N	N	N	N	N	N
	NM	**NY**	**NC**	**ND**	**OH**	**OK**	**OR**	**PA**	**RI**	**SC**
AGENCY PERMIT	N	Y	Y	Y	Y	N	Y	Y	Y	Y
AGENCY PROVIDES INFORMATION PACKG	N	N	N	N	N	N	Y	Y	N	N
	SD	**TN**	**TX**	**UT**	**VT**	**VA**	**WA**	**WV**	**WI**	**WY**
AGENCY PERMIT	N	N	Y	N	Y	Y	Y	N	Y	N
AGENCY PROVIDES INFORMATION PACKG	N	N	N	N	N	N	N	N	N	N

CHAPTER 2
MECHANICS OF UNDERWATER EXPLOSIONS

INTRODUCTION

Underwater blasting is a science well understood in direct terms. The chemical and physical effects of detonation are well known. Wave passage is accurately developed in theory. The application of explosives and blasting agents is an art, because it is expensive to study in detail and because the variability of the media exposed to detonation waves is extremely complex. Testing explosives or utilizing the detonation in some manner can easily be accomplished by the art of blasting without fully understanding, or needing to understand, the science and details of detonations and wave passage. The physical aspects of underwater blasting are described herein; more complete treatments of underwater blasting may be found in Cole (1948) and Mellor (1986).

Three aspects of blasting are the detonation, the media transmitting the blast effects, and the effects of blast on its ambient environment. Some blast effects may be the desirable reasons for the shooting (examples, removing a bridge pier, explosive/ordnance testing, producing seismic waves). Other effects may be adverse impacts, resulting in damage to the natural and/or built environment. The primary interest of this document is the passage of the water-borne pressure waves and its negative impacts. These pressure waves are produced in water when the explosive charge is in the water column or when the shot is beneath or adjacent to the body of water.

Underwater blasting is conducted for a number of uses: rock excavation, demolition, grade preparation for foundations, structural rehabilitation, waterway applications (deepening channels/harbors, dike removal, and emergency levee-raises during extreme flooding), geophysical exploration, fish sampling, metal forming, military operations, and other uses. Shock-wave pressures in column from explosions can have adverse impacts on nearby submerged structures and on aquatic life. Regulatory agencies, depending on the circumstances, do not permit underwater blasts (nor blasts near aquatic environments) without mitigation of the adverse effects of pressures.

EXPLOSIONS

Modern blasting products release energy in two forms: <u>detonation</u> and <u>burning</u>. Detonation is the term for the rapid pressure front moving through the explosive ahead of a chemical transition front. The property of detonation makes that particular formulation an explosive, such as Cyclonite (RDX) and Trinitrotoluene (TNT). RDX is a primary explosive, only a small quantity of RDX is required to begin detonation. TNT, like dynamite, is a high explosive, which start to detonate only when a greater amount than critical volume or critical diameter is present. A blasting agent is a term for a material that can be made to detonate when initiated properly, examples are Ammonium Nitrate with Fuel Oil (ANFO) and Water Gel Slurries. A minimum charge diameter is required to achieve and sustain detonation. Dick et al. (1993a) shows that some dynamites require less than 20 mm diameter to initiate detonation, ANFO requires a 50 mm diameter with confinement to detonate. Burning (deflagration) releases the chemical energy of the materials, including explosives, but more slowly. Deflagration occurs without the rapidly expanding, detonation pressures. Black powder is a material that only deflagrates and has been called a low explosive. High explosives and blasting agents burn when their charge diameter is less than the critical diameter to achieve detonation.

The chemical energy of a detonating explosive is released as physical, thermal, and gaseous products. The detonation wave rapidly densifies the explosive material.

This physical shock front moves faster than the acoustic velocity of the explosive material. The detonation is only sustained within the limits of the explosive. The detonation ceases at the boundary with the medium containing the explosive. The shock wave passes into the medium. The thermal and detonation effects are only important near the explosion. Consideration of the thermal and detonation impacts may usually be ignored beyond a short distance (three to ten diameters of the explosive's volume) from the blast. The two main impacts in the far field (beyond the zone where thermal and detonation effects are important) from an explosion are the shock waves and the expanding gaseous reaction products. The original shock wave is the primary cause of damage to aquatic life or other structures at great distance from the shot point. The expanding gaseous products can cause: a noisy airblast pressure concussion when exploded in the air, but produce little shock wave amplitude in surface water or earthen media; a water plume and/or a gas bubble for blasts in the water column, and less intense, recurring pressure waves when a pulsating gas bubble occurs; and, lengthening of fractures and displacement of solids when a confined explosion occurs in sediment or rock.

Water is displaced and pressurized both by burning and detonation within the water column. Water is somewhat compressible in the near-blast region by extremely elevated pressure due to the explosion. The water column depth and work accomplished by the blasting (due to its confinement) are significant conditions in determination of the explosion's effects. Besides the compression waves produced by the explosion, other impacts could include noise, projectiles and gaseous chemical products, which are vented to the water or air. Water is nearly incompressible at standard temperature and pressure and cannot support shear waves. The extreme pressures and temperatures of explosives' detonation complicates the analysis of their adverse effects.

Use of explosives within or beneath or adjacent to the water column requires a greater effort of safety and planning, relative to blasting under dry conditions. The greatest concern is worker safety. The safety of underwater blasting is directly related to planning and safe work practices. Worker safety must be paramount in mitigation planning to avoid the severe potential that could result in accidental detonation. Accidental detonation could shoot a large quantity of explosives, cause worker mortality, and create greatly increased losses in the natural environment. The variety of other concerns includes water flow rate, turbidity, floating debris, and working depth beneath the water surface. Maintenance of exact horizontal spacing within and between rows of shotholes and loading explosives overwater increases the difficulty of accurate shooting. These limitations also compound the potential for misfires and overshooting. With submerged shooting, the chance of crossfiring closely spaced holes or overloading voids/crevices in the material contribute to the increased pressure and energy in the shot.

Important underwater blasting parameters include, but are not limited to: types of explosives and their properties; energy releases from underwater explosions - amplitude, duration, frequency, pressure, impulse, energy flux density; charge weight and explosive-gas diameter versus water column depth; unconfined test explosion properties versus confined blasting to perform work; scaling laws of underwater blasting; wave mechanisms - spherical, cylindrical and planar wave propagation; and, measuring equipment and its calibration.

Explosives perform two types of mechanical work: material fracturing (crushing and extending fractures) or material displacement. Both shock and gas energy are released by the detonation process. Varying explosive types release differing total energy and fractions of the shock and gas component energies. All detonations have some fraction of both brisant (shock) energy and expansion (gas) energy. The shock component may be used for unconfined explosions, as the gas energy is lost to the ambient environment without confinement. Common, unconfined applications in the

water column include explosives/ordnance testing, severing steel members, seismic exploration sources, and boulder breakage. The more useful component for more typical blast applications is gas development. These typical applications are mineral production or mass demolition by placement of explosives in boreholes with stemming. Stemming is the (normally granular) fill material placed in the boring over the explosives material and extending to the surface. [For rock quarrying, the impedance (density times velocity) are matched between the rock and the explosive. Higher impedance explosives typically have more shock energy.] The expanding gases displace material volumes when placed in such confinement that the gaseous reaction products are not quickly vented to the atmosphere or marine environments.

Commercial explosives and blasting agents are designed as oxygen-balanced chemical reactions (Dick et al. 1993b). The explosive's fuel and the oxidizing agent achieve the greatest energy of reaction when there is neither an oxygen debt nor surplus. The importance to underwater shooting is that a poor reaction is further water cooled or "dampened" to make the reaction energy lower than if conducted above the water surface. Unbalanced, water-cooled detonations may produce excess amounts of toxic gaseous products, besides not achieving the desired work.

Two factors are important to underwater blasting: increasing charge weights and lowering shock energy. Brower (1977) cites the need to displace both the blast's host material and water to produce the desired outcome in typical work. The placed weight of explosives is commonly increased several multiples in comparison to the same work effort above the water surface. Oriard (1983) questions the need for greater charge weights and recommends increased burden for greater water depths. While shock energy may be important to fracture the media to be displaced, gas energy must be capable of moving the material and the water load. Explosives in underwater blasting obviously should be selected, in part, by the fraction of available gas energy. Further, the shock energy component causes the peak, shock pressures. For underwater blasting, this brisant pressure wave and its negative, reflected pressure component at the air-water surface are the chief parameters in undesirable damage to structures and aquatic life.

Optimized blasting is the environmental awareness of the impact of blasting on the objective and ambient media. It also recognizes the host medium has a primary effect on the blasting efficiency. Controlled blasting (Konya and Walter 1985) is an industry term that is similar to, but different from, optimized blasting. Optimized blasting utilizes the media's properties, i.e. varying the shooting pattern to take advantage of the bedding and jointing of the removed rock, to achieve efficient production. Optimized blasting attempts to optimize the production and diminish the effects on the surroundings. Optimized blasting for underwater programs: reduces the total weight of explosive by carefully considering the media and the blasting pattern's relationship to the material's properties; increases the number of delays used to allow movement of material (reducing the burden) prior to causing additional material to displace; and, increases confinement with added stemming to assure that premature venting of gases does not occur.

Blasting materials are rated by a variety of factors, many of which have little commonality between manufacturers. The producers provide the values of common properties to the purchasers of explosives and blasting agents. Konya and Walter (1985) and Persson et al. (1994) describe the array of explosives' and blasting agents' properties. The properties of selected explosives can enhance performance and reduce the hazards of blasting. For the considerations herein, the shock energy should be diminished to limit the pressure pulse reaching the surrounding media. The maximum shock pressure at some distance from the blast is related to the detonation pressure, the travel path and the media of passage.

a. Density. The density is the mass of the product per unit volume, usually expressed by Specific Gravity (SG_e). The more dense the explosive the greater the power of the shot. SG_e can vary from 0.5 to 1.7 (Dick et al. 1993a). An explosive is easier to handle and place submerged, if it is heavier than water, $SG_e > 1.0$. Density is one of two factors contributing to the detonation pressure within the detonating material.

b. Detonation Velocity The detonation velocity (v_e), by title, is the propagation rate through the detonating media. The v_e ranges from 1,900 to 7,500 meters/second (mps). Konya and Walter (1985) provide an equation for the detonation pressure, P_d, [converted to metric units]

$$P_d = 4.50e\text{-}4\ SG_e\ V_e 2 / (1. + 0.80\ SG_e) \qquad \{1\}$$

where the pressure units are megapascals (Mpa, see Table 2.1 for common pressure conversions) for V_e in mps. The peak pressure at the wall of the explosive's containment (typically a borehole) may be one half the P_d , while Konya and Walter (1985) feel that the detonation state does not exist at this boundary. The shock pressure due to the P_d must extend to the surrounding media, and is related empirically to the wall pressure and, ultimately, to the P_d.

Table 2.1. Pressure Unit Conversions

	kPa	bar	psi	atm
1 kPa	1	.0100	.1450	.009869
1 bar	100	1	14.50	.9869
1 psi	6.895	.06895	1	.06803
1 atm	101.3	1.013	14.70	1

The compression-wave pressure at any location in the water column is related to the shock pressure in the detonating material. Since the maximum pressure, P_m, within the water is the cause of hazard, its relation to P_d and to the square of V_e is extremely relevant. The need to fracture a mass prior to its displacement (an explosive with large shock energy) is an argument some authors and blasters make. Contrarily, Dick et al. (1993a) indicates that "typical of most operations, it is of little importance." Given two explosives of the same charge weight, A with a V_e of 4,250 mps and B with a V_e of 6,000 mps, the P_m for explosive B would be twice the P_m value at the same distance as for A. Thus, an explosive with a low V_e should be considered for submerged shooting when the hazard of shock pressure is a concern. The doubling of pressure is contrary to unpublished data by Keevin (1995) that three commercial explosives of differing V_e produced similar pressures and the same mortality in fish for unconfined, shallow, water-column shots. Other factors may be more important in reduction of the shock-wave pressures (Oriard 1983).

c. Fumes. Fumes are the toxic gaseous by-products (chiefly carbon monoxide and nitrous/nitric oxides) of the detonation reaction. The fume class or quality for each blasting compound is a relative measure from poor (excessive toxic gas creation) to excellent (insignificant toxic gas production). Some of these toxic products remain as a dissolved hazard in the ambient water body, which may have a detrimental effect on aquatic life. Underwater blasting creates conditions that may

lead to increased fume production: inadequate water resistance and inadequate priming (Konya and Walter 1985). "Permissible explosives" used in underground coal mining should not be considered an alternative explosive for underwater blasting. Permissible explosives are purposely less efficient, cooler reactions to avoid igniting coal dust, and have worse fume quality than other blasting materials.

MEDIA CONSIDERATIONS

Blasting in solids beneath or adjacent to the water column is normally conducted to remove obstacles. [Some removal methods may have the charge resting on the solid's surface in air or in water.] Explosives are placed typically in boreholes drilled into the mass to be removed. The shock front travels most rapidly down the centerline of the explosive column. Detonation proceeds more slowly at the boundary of the explosive with its container and passes into the surrounding medium. The shock wave, after passage into the enclosing material, does work crushing, fracturing and/or compressing the material. The loss of the energy supply, use of energy to produce work on the medium, and the ever-expanding surface of the compression front causes the shock wave to slow to the sonic velocity of the medium. Particle disturbance at this transition distance from the explosive becomes the commonly known compression or Primary wave (P-wave). The shock wave within the supersonic zone, called the near field, exceeds the elastic strength of the medium producing fractures and permanent deformation. The P-wave beyond the transition distance, termed the far field, remains within the elastic limits of the material (causing no lasting effects in rigid solids).

Seismic exploration, fish sampling, military use and explosives research may be conducted by blasting in the water column (open-water shot) of natural environments. Explosions in the water column produce P-waves in the far field. The P-waves originate from the shock wave. P-waves also are created from the contraction points of the pulsating gas bubble of gaseous reaction products, when the gas bubble does not reach the air-water surface before reaching its contracted state.

The more important differences between water-borne blasting and shooting within solids are the properties of water. Water's elastic moduli are not nearly as great as solids and, by its nature, water (like all fluids and gases) does not support shear waves.

The shock wave emanating from the explosive's detonation is "converted suddenly into potential energy of compression and kinetic energy of outward motion in the water medium" (Kramer et al. 1968). Cole (1948), in his landmark publication, describes the important processes and subsequently develops analytical and empirical equations of state for the expanding waves. The shock wave expands into the surrounding water medium applying a compressive load to the water. In a planar shock front, the amplitude of the pressure pulse will retain its size for some distance. Cole (1948) indicates that the particle velocity, u, is related to pressure, P. by

$$u = (P - P_o) / Z_w, \qquad \{2\}$$

where the hydrostatic pressure is P_o and the acoustic impedance, Z_w, is the density times the velocity of water.

The pressure amplitude for cylindrical and spherical wave forms diminishes with radial distance from the explosive. The nonplanar explosions produce two elements of the original waveform: the shock wave (or compressive flow) and the afterflow, or surge. The ever-expanding radial volume affected by the shock front must act

also tangentially to compensate for the "side load," called spherical divergence. It is this side pressure accommodation that contributes to the second term, surge. These two effects, shock and surge, occur simultaneously along the shock wave path to the transition distance. Beyond the transition distance, the velocity of the disturbance falls to the P-wave velocity for water and the surge term has become infinitesimal. The transition distance bounds the near-field region where acoustic radiation and afterflow are important from the far-field where only compressive flow is a factor.

A gas bubble or, as Cole (1948) terms it, gas sphere expands from the gaseous products of detonation well after the shock wave has passed. The gas bubble with its momentum expands to a maximum value, if the explosion is sufficiently deep so that the bubble does not break the water surface with the atmosphere. Bjarnholt (1978) provides a term for the maximum bubble radius, a_b, in m:

$$a_b = [1.3\ Q\ W\ /\ (1 + 0.1\ d_w)]^{1/3} \qquad \{3\}$$

for Q as the heat of detonation in megajoules/kilogram (MJ/kg), W being the charge weight in kg, and d_w is the explosive's water depth in m. Bjarnholt (1980) gives Q for a variety of explosives; for an estimate of a_b use a Q of 4.44 or 4.27 MJ/kg for Nitromethane or TNT, respectively.

The gas expansion forms an oscillating system with the gas' momentum and hydrostatic pressure of water. The gas bubble initially extends beyond the equilibrium state with the water load. The gas sphere cannot easily rise toward the air-water surface while in its larger size, because of the great volume of water that must be displaced for the bubble to rise. The surrounding water pressure causes the bubble to rapidly shrink to a minimum size of much greater dimensions than the original solid explosive's volume. The gas sphere at this contraction has greater internal pressure than the ambient water pressure, and expands a second time. A smaller shock wave is released at the instant the bubble is at its minimum diameter, in transition to its expansion phase. The gas bubble rises quickly while in the compressed volume. The oscillation in size continues until the gas sphere breaks the surface with episodic releases of energy and rapid vertical displacement at gas-volume minima. Cole (1948) shows that the period of bubble oscillation is a function of d_w, Q. W and fraction of remaining energy for the nth bubble oscillation, f_n. Cole indicates that the energy remaining is merely 14% and 7.6% for f_1 and f_2, compared to the total energy.

Pressure. The pressure between the dominant shock energy and the pulse from the gas sphere takes a declining exponential form. Depending on the distance from the blast, the pressure outside the explosive rises to a maximum pressure, P_m , in microseconds (μ s). USACE (1991) and Joachim and Welch (1997), in a form similar to that provided by Cole (1948), give the value of pressure in time after reaching the peak (P_m) as

$$P(t) = P_m e^{-(t - ta)/\Theta} \qquad \{4\}$$

for t_a as the arrival time and Θ , the time constant. USACE (1991) and Joachim and Welch (1997) give the equations for the parameters of {4} [which herein have been converted to metric units].

$$P_m = 53.1\ R_s^{-1.13} \qquad \text{[MPa]} \qquad \{5\}$$

$t_a = r / c_w$ {6}

$\Theta = 9.2e\text{-}5\ W^{1/3}\ R_s^{\ 0.18}$ [s] {7}

$R_s = r / W^{1/3}$ [m/kg$^{1/3}$] {8}

Equations {5} through {8} use the lateral distance, r, in m, pressure in MPa, time in seconds (s), velocity in mps, and equivalent weights of TNT in kg. R_s is the scaled range, the distance normalized by the explosive weight factor. USACE (1991) and Joachim and Welch (1997) give the TNT-equivalence for several explosives types and, in particular, the 1.1 weight conversion for Nitromethane. Medwin (1975) provides an equation for the sonic velocity of water (in mps) as a function of depth (d_w), temperature (T), and salinity (S) in parts per thousand (ppt).

$$c_w = 1449.2 + 4.6\ T - 0.055\ T^2 + 2.9e\text{-}4\ T^3 + (1.34 - 0.01\ T)(S - 35) + 0.016\ d_w\ \text{[mps]} \qquad \{9\}$$

for O m < d_w < 1,000 m, 0 ppt < S <45 ppt, and 0° < T < 35°C.

Scaled range, R_s, is an important term. R_s allows the comparison of differing explosive weights. It provides the means to "scale" the pressure, vibration, and mortality effects of blasts. The distance of comparison will need to be large enough to be well beyond the transition distance, in the far field, for the larger explosive weight. Equation {8} indicates that the same effect will occur at double the distance when the charge weight, W. is cube of two, or eight times, greater. The blast effect (pressure or mortality) will be the same at about twice the distance for: 16 kg replacing 2 kg of the same explosive material; 80 pounds (lb) substituted for 10 lb; and, 3,200 kg replacing 400 kg.

Equation {4} is an empirical form and does not resolve the variation of pressure due to boundary effects nor time duration to the bubble pressure arrival. The pressure in very deep water without nearby surfaces will fall below P_o termed "negative pressure," due to the inflow of water on the collapsing gas sphere. Negative pressure merely indicates that the ambient pressure falls below the gage hydrostatic level. The pressure does not decline below zero absolute pressure, as water has minuscule tension capacity. Other travel paths of the shock wave can complicate the waveform, when approaching other surfaces. Figure 2.1, reproduced from USACE (1991), shows the four major wave types affecting pressure at a point. The first arrival at some location in the water column due to a blast also in water (when the shot is well removed from a higher velocity bottom material) is the direct wave. The upper wave of Figure 2.1 shows its rapid rise and the decay form of equation {4}. After some additional time there will be two (or many more multiple) reflections. The reflection off the air-water interface is negative, due to yielding (displacement) of the surface. The air-surface reflection is of nearly the exact amplitude as the direct wave, because of the impedance contrast with air. As shown in Figure 2.1, the air-surface reflection arrives later than the direct arrival, due to the added distance traveled in reflection. The bottom surface is not a perfect reflector; this surface accepts energy, so the bottom-reflection's amplitude is less than the direct wave's. The amplitude from the bottom reflector is in the same positive sense as the direct wave for the bottom and will not yield in displacement, like the air-water surface. The bottom reflection is shown third in Figure 2.1. The arrival of the two reflections depends upon where in the water the shot and receiver are located. For Figure 2.1, the shot/receiver locations are much nearer the air surface than the solid bottom. The bottom medium refracts some energy and, at a critical refraction distance (for a bottom medium's acoustical velocity exceeding the speed in water), induces a refraction wave that imparts

energy back into the water. The refraction wave is the fourth in Figure 2.1. The resultant wave for the assumed geometry of the example is the lowest graph. This example does not show possible multiple reflections between the air surface and the bottom, nor arriving bubble sphere peaks.

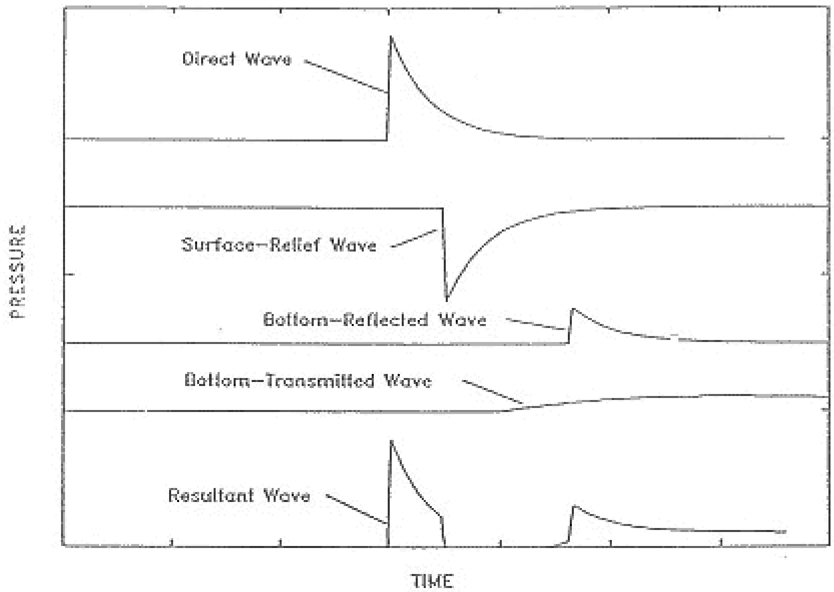

Figure 2.1. Shock-wave components and resultant wave (USACE, 1991)

Blasts created by an explosion located near the air surface have no oscillating bubble of explosion gases. The gases will be vented to the air as a column or plume, when $d_w < a_b$. There will be no latter pressure wave arrivals in this case from a gas sphere. Bottin and Outlaw (1987) provide an estimate of the water plume radius, a_p, [converted to a metric relation]

$$a_p = 18.9\ W^{1/3}\ (d_w + 10\ m)\ [m] \qquad \{10\}$$

for W in kg and d_w in m. A column of water and gas is ejected into the air of radius apt The displaced water column extends to the hemisphere of like radius, centered at d_w. The water rushing to replace the vented plume volume can cause adjacent negative gage pressures from the venting gas and water displacement long after the shock-wave's passage.

The explosive's shock energy, when sufficient, can produce a sizable "cavitation hat" near the air surface just beneath the water. Cavitation is the negative gage pressure effect exhibited by explosives near the air-water surface and by boat propellers. The cavitation is caused by the tensile movement in the water toward the air. The proximity to the air surface assures that there will be a negative pressure reflection as part of the wave form. The P_m using equation {4}, is 9 MPa for just 10 g (not kg) of high explosive. In perspective, this is 90 times the atmospheric pressure of 0.1 MPa; thus, the air-surface reflection of a tiny explosive weight will produce negative pressures. The water near the surface can only accommodate a gage pressure of -0.1 MPa, but the reflection attempts to produce pressures to -9 MPa and results in cavitation. Christian (1973) defined the cavitation's cylindrical volume of radius, R_c, and thickness from the air-water surface to depth Do (not to be confused with the explosive's charge depth, d_w). This "cavitation hat" is a flattened disc of diameter $2R_c$, centered vertically above the

midpoint of the blast. There is a potential within the cavitation hat for overextending air-filled organs due to the negative pressure; this damage potential can produce organ damage or mortality. By equations, Christian reports [converted to metric units]:

$$0.036\ d_w^{1/2}$$

$$R_c \approx 40\ d_w^{1/2}\ (2.2\ W)\ [m] \qquad \{11\}$$

$$D_c \approx 3\ W^{0.3}\ [m] \qquad \{12\}$$

for $d_w \leq 15$ m and $W \leq 450$ kg.

Impulse. Empirical estimates of pressure, strength and energy were required prior to the recent development of accurate and inexpensive recording equipment. Piezoelectric pressure transducers, commercially available only recently, can measure these large, rapid pressure wave variations. The strength, or impulse, of the wave is its momentum as it crosses a surface. The integral of pressure over time is momentum per unit area and is called impulse, I.

$$I = \int_{ta}^{t'} P\ dt \qquad \{13\}$$

The units of impulse are merely pressure-time, e.g. Pa-s. The impulse is the area under the pressure-time curve, for example the bottom graph of Figure 2.1. The length of time to evaluate the integral depends on the purposes and geometry of the blast. Cole (1948) recommends $(t' - t_a)$ be 6.7Θ , but he accepts that this is arbitrary. Cole (1948) chose 6.7Θ to resolve the strength in only the wave's exponential-decay portion prior to the bubble pulse. Gaspin (1975) and some subsequent authors use a long integration time without clearly stating their method of period evaluation. Different authors calculate impulse over varying periods and use either or both the positive pressure interval and the negative gage pressure duration. The decision for the integration period must account for the blasting's intent and waveform complexities. Cole (1948) estimates [converted to metric form]

$$I(6.7\Theta) = 7.41\ W^{1/3}\ R_s^{-1.05}\ [kPa\text{-}s] \qquad \{14\}$$

for W in kg and R_s in m/kg$^{1/3}$. USACE (1991) and Joachim and Welch (1997) furnish an impulse estimate without specifying an integration interval [converted for metric values]:

$$I(t) = 5.75\ W^{1/3}\ R_s^{-0.89}\ [kPa\text{-}s] \qquad \{15\}$$

for W in kg and R_s in m/kg$^{1/3}$. A much more accurate determination of strength is provided by obtaining pressure readings at about 1. μ s intervals for the full pressure range and integrating the pressure record in time by {13}. While this latter method is preferred, there are many difficulties in properly recording the pressure wave with pressure transducers (USACE 1991, Joachim and Welch 1997, and Hempen and Keevin 1997).

Energy. Shock-wave intensity is assessed by determining the energy flux density, E. The intensity is a measure of flow or change of energy across a unit surface "normal to the direction of [wave] propagation" (Cole, 1948). Cole develops E for

both shock-wave terms of compressive flow and afterflow as components of one formula. He proves that the surge term theoretically is negligible beyond 10 to 20 times the effective explosive's charge radius (a_e). Cole (1948) gives

$$E = Z_w^{-1} \int_{ta}^{t'} P^2 \, dt \qquad \{16\}$$

the intensity as for $P \leq 135$ MPa. E is in units of J/m^2 for Z_w in SI units. The units of intensity are energy or work per unit area. Cole recommends the same integration period of 6.7Θ for E. The integration period should be determined by the intent of the blasting, like the discussion above for impulse. Cole (1948) approximates the intensity as [converted for metric values]

$$E(6.7\Theta) = 105\, W^{1/3}\, R_s^{-2.12} \; [J/m^2] \qquad \{17\}$$

for W in kg and R_s in $m/kg^{1/3}$

The integrals of equations {13} and {16} accurately resolve the strength and intensity of the shock wave at any point in the water column where pressure is measured. Both formulae are correct when the explosion is mid-water or when the shot is embedded, because each measures its parameter based on the pressure wave recording at the point of interest. The empirical formulae are estimates for the water-column shots at best, and are not intended to represent explosions in solids overlain by a water mass.

TRANSMITTING MEDIA

Explosive shooting is conducted in solids beneath the water surface for removal or demolition uses. The work accomplished by the gas expansion phase is energy consumed. Less gas energy can be converted to P-waves to enter the water, since the gas bubble will not pulsate as it rises. Conversely, the shock energy rapidly disturbs all surrounding environs. The P(r,t) for the first arrival must be resolved by the properties of the blasted medium, blast geometry, and wave transmissions across boundary surfaces.

The propagation of waves across surfaces between media has been developed by text authors, such as Kinsler and Frey (1950) and Grant and West (1965). Oriard (1985) shows that the energy transmitted to water from rock of specified properties varies from 0.0 to 0.37 of the total shock energy for varied angles of incidence (Figure 2.2). Oriard (1985) shows that for land-based blasting adjacent to a water body the pressure wave's amplitude "is about 1/40 to 1/400 of" that amplitude which would be calculated for perpendicular (0.°) incidence between water and ideal rock. Shock-wave energy would be considerably greater when the blasted medium is directly beneath the water column. In this latter case, 30% to 37% (for 30° down to 0° incidence, respectively) of the generated energy enters the water. Blasting would not usually be accomplished in weak material of low P-wave velocity and Elastic Modulus. The solid's properties would almost always be significantly greater than water's, thus the pressures and energies should be comparable to those of Figure 2.2, in general. At large incidence angles (greater lateral distances from the blast within a submerged solid), less energy enters the water from the solid, but the water-borne energies from directly above the shot persist in the water beyond the critical refraction angle. For the case cited by Oriard in Figure 2.2, this angle is 19.1° (Grant and West 1965). The water column acts as a wave guide at incident angles within the water greater than the refraction angle while continuing to receive energy from the solid. In other words, some energy at large lateral distances from the shot is captured and retained by the water column.

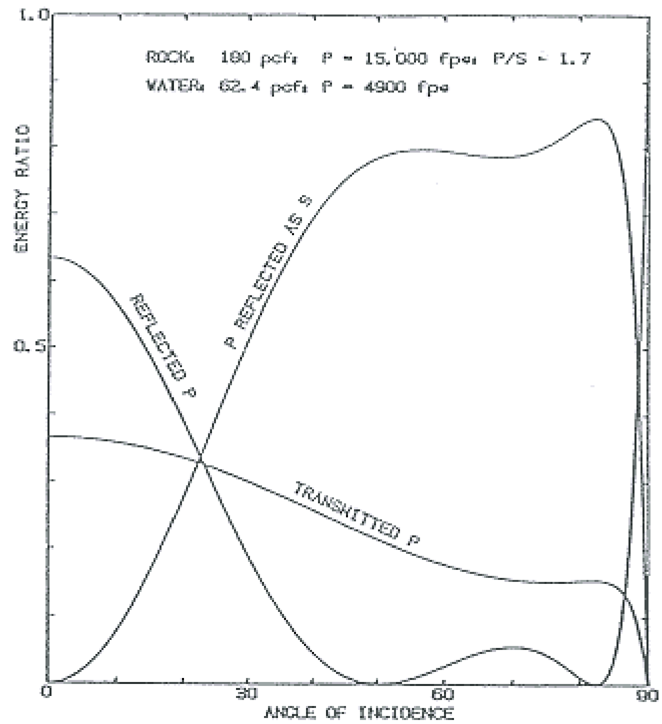

Figure 2.2. Relative energy entering the water column from a rock material versus the incident angle at the boundary (Oriard, 1985)

Another consideration of the shock wave from a solid-confined blast is the direction of the explosive's detonation. Initiation of shots is normally at the deepest part of the explosive charge. The detonation begins near the bottom of the boring and continues to propagate up the explosive column toward the surface. The detonation wave is focused toward a narrow cone in the direction of travel. Less shock energy is transmitted radially and only a small percentage of shock disturbance emanates opposite the detonation direction (Konya and Walter 1985). The shock wave from the completed upward detonation is focused toward the water column. Thus, the strongest intensity of shock energy in the water column is directly above the blast for a confining solid. The shock energy crossing the boundary, which is generally normal to the explosive's placement borings, into the water is the largest (0.37 for the cited example) of all the transmission angles.

Blasting in a solid beneath the water surface allows gas energy to be released to the water. The extreme cases for gas energy production are comparable to two scenarios: the blast detonated in the water column (maximum gas energy contribution) and the explosive shot within a material of sufficient strength to retain the blast products. There is no gas energy component for a mid-water explosion, if the explosion occurs within a container that totally contains the reaction gases. There would also be no oscillating gas bubble since the container retained the expansion products. All the work (in actual production blasting) accomplished by the detonation's gases in moving the solid mass is work that cannot contribute to bubble oscillation energy release in the water column. Premature venting of the explosives' gases reduces the displacement of the mass and imparts this gas energy to the water column. Having sufficient stemming (the granular filling from the top of the blasting material to the top of the borehole) length eliminates the early release of the detonation's gases.

<u>Shallow Water Environments</u>. The term "shallow water" may be defined for several circumstances. A useful consideration relates water to its sonic velocity. Relationships to blasting could be used to define what is shallow. Lastly, shallow

can be defined by the blasting objective and limitations on the depths of mitigation.

Equation {9} shows that velocity is heavily dependent on water temperature and pressure, or depth. Several naturally occurring temperature layers exist in bodies of water. Urick (1983) indicates that four major layers may exist: surface layer, seasonal thermocline, main thermocline and deep thermocline. A thermocline is a unit of water which has a uniform gradient of temperature (and dissolved oxygen) with depth. The surface layer produces a daily variation of water's sonic velocity; It's velocity may be constant or variable with depth. Beneath the surface layer lies the tier of the seasonal thermocline, which has an annual variation and a negative thermal (and velocity) gradient. In deeper bodies of water, the main thermocline develops with a nearly permanent, uniform negative gradient. The deep isothermal layer occurs in waters below the main tier (occasionally below 1,000-m depth - Urick 1983). The deep isotherm has a roughly constant temperature of 4.°C and its increasing velocity with depth is due to hydrostatic pressure. Shallow water depth may mean the level above the interface of the main and deep thermoclines, if they exist. At this surface, water's velocity is a minimum and refractions above or below this horizon tend to remain on their increasing velocity side. Shallow may mean the depths of water bodies that do not develop a main thermocline. For impoundments without main thermoclines, shallow may be the depth of the winter velocity minimum.

Shallow water depth in conjunction with blast parameters may apply to depths above which no gas sphere develops or may be considered the lowest depth of the cavitation hat. Both of these shallow depth definitions depend on the explosive's weight. The greater the instantaneously shot charge weight, the deeper the allowable depth to avoid venting of the reaction gases or by equation {20} the greater is D_C . A reduced environmental impact occurs for low detonation velocity explosives with sizable gas energy components. None of the vented reaction gases may oscillate in the water column for these reduced impact explosives with significant confinement. By this gas energy definition of "shallow," the correct choice of explosive and confinement parameters would result in great depths with no gas energy contribution of pressure to the water column.

Shallow water depth may be defined by the working limit of typical underwater blasting. Only occasional, special purpose blasting for engineering work would require blasting deeper than 20 m for even oceanic harbors. Location of borehole positions would be more difficult at this 20-m water depth. Harbor depths are infrequently maintained below 15 m. Tunnel or mineral blasting beneath water bodies is conducted at much greater depths, but the blast displaced solid mass is not exposed to the water body. Shallow water at depths within (an arbitrary) 20 m of the water surface represents herein the relative ease of conducting blasting work, or its more frequent use, and the zone of increased environmental harm.

PRESSURE-WAVES

Shock waves from underwater blasting are of interest not only from an academic sense, but also because they may be important to blast production and damage due to explosive use. The explosive selection has a bearing on both the production and damage potential. The hole diameter, for example, for charge placement is related to the minimum removal height, called the bench height, by the "Rule of Five" (Konya and Walter 1985). Minimum bench heights of 3. m require 50. mm, or smaller, diameter holes. There are fewer blasting agents with small critical-diameter sensitiveness that will detonate in this hole size. Both dynamites and water gels meet the sensitiveness criterion and are water resistant; however, dynamites have higher detonation velocities (Dick et al. 1993a). The choice of a water gel blasting agent would lead to less shock energy, and therefore less aquatic mortality potential, while allowing proper rock breakage.

> In practice, nearly all underwater blasting will be done with holes larger than 50 mm, regardless of depth. The greatest expense is that associated with drilling, and that expense is dramatically reduced by drilling holes of larger diameter on wider spacings (Oriard, 1983).

Brower (1977) was one of the earlier authors to recognize:

> The two basic reasons for restricting or limiting the water shock levels are: (a) preventing damage to nearby structures and (b) minimizing environmental damage.

Brower was concerned with both structures and fauna. While other authors had one concern or the other, Brower recognized the need to mitigate both. Brower provides Cole's estimate for P_m like equation {6}. Brower's provisions to moderate water shock were limited to care with the actual blasting measures.

Effects on Structures. Several authors estimated blast effects on structures by pressure waves, as related to the Pm and impulse (I). Langefors and Kihlstrom (1978) emphasized that the reduction of both P_m and I are important to the safety of structures. Oriard (1983) presented:

> ...the damage potential of underwater waves is not directly related to the peak pressure, but to impulse... it may be more damaging to lengthen the duration of the pressure pulse than to lower its peak pressure depending on the characteristics of the structure in question.

Oriard (1992) suggests that dynamic strain cannot be related to the static stress regime of most analyses. He also implies that negative pressures from venting (and from cavitation) cause plucking from tension at the concrete-water interface.

Structures should be addressed like the Oriard (1985) analysis to estimate dynamic stress and strains on the submerged form. Oriard (1985) chose a procedure of conducting small production shots to evaluate "the pressures in the water adjacent to the powerhouse walls and stoplogs." This allowed the development of one program to full scale without damage to the extremely important adjoining structures.

CHAPTER 3

THE ENVIRONMENTAL EFFECTS OF UNDERWATER EXPLOSIONS: AQUATIC PLANTS

INTRODUCTION

Aquatic plants, both submerged and emergent, have great importance as a food source and shelter for both aquatic (Rozas and Odum 1988; Lubbers et al. 1988) and terrestrial organisms (Bellrose et al. 1979). Extensive damage and mortality to aquatic plant beds resulting from an underwater explosion could possibly upset the balance of the ecosystem being altered.

DAMAGE AND MORTALITY OF AQUATIC PLANTS EXPOSED TO UNDERWATER EXPLOSIONS

Data on the effects of underwater explosions on aquatic plants are very limited. Ludwig (1977) used explosives as a "herbicide" to remove eelgrass (Zostera marina) to create a channel within the Niantic Estuary at Waterford, Connecticut in an attempt to improve water quality and containment of egg and larval stages of the bay scallop (Argopectens irradians). A contractor demonstrated the efficiency of eelgrass removal techniques with in situ observations being performed on the detonation of single and multiple charges as well as a weighted length of detonation cord alone. During an eight week period following the explosions, the eelgrass experienced an orderly dieback. In no instance was the disappearance less than complete along an expanding circle of defoliation. In the case of the single charged detonations, the circular defoliation had a final diameter of approximately seven to eight meters. The chain or string detonations created overlapping rings of impact ultimately clearing a rectangular area approximately 40 m long and 7 to 8 m wide. The detonation cord created a similar impact but the final zone of influence was limited to approximately 2 to 4 m of total width. Unfortunately no information was provided concerning the charge type or weight.

Removal was restricted to eelgrass, with green algae (Codium sp.) and rockweek (Fucus sp.) thriving in the defoliated areas following eight weeks. Ludwig (1977) hypothesized that the orderly species-specific defoliation was the result of a disruption of the cellular structures within the rhizomes. As the cellular destruction radiated outward the thallus structures separated in a manner reminiscent of normal exfoliation during the late autumn or winter period. Examination of the rhizomes, however, clearly indicated cell wall failure internally while the epidermal fibers continued to hold the structure together.

Without explosive weight information or pressure wave data it is impossible to compare aquatic plant mortality levels with other aquatic organisms.

Smith (1996) examined the effects of underwater explosions on two types of aquatic vascular plants (emergent and submerged), and three algal species. Two species of vascular plants (Ludwigia peploides (HBK) Raven and Myriophyllum heterophyllum (Michx.)) and three algal species (Chara zelandica (Willd.), Chara contraria (A. Braun), and Nitella acuminate (A. Braun)) were exposed to 2 kg of T-100 Two Component (green stick) explosive with a #8 instantaneous electric blasting cap. Explosive charges were suspended from a float to a depth of 1.5 m below the water surface. Plants were placed in hardware cloth cages and set out at 2.5, 4.5, 6.5, 8.5 and 10.5 m from the blast. Cages were attached to a buoyed rope of appropriate length to maintain the cage centers at a depth of 1.5 m below the water surface. A control cage contain each of the plant species was used for each blast. Controls received the same treatment (i.e., transported to and from the blast area) as

experimental plants with the exception of exposure to blast pressures. Each test was replicated (test blast 1 and test blast 2).

Plants were weighed pre-test and exposed to the test blast on September 30, 1996. All plant material remaining after the explosions was transported back to the laboratory and re-weighed, using the same procedures as before the blast. Plants were maintained in 10-gallon aquaria in a greenhouse. At the end of the first week, plants were removed from the tanks and all dead tissue was removed. Remaining plant tissue was weighed and recorded. This procedure was repeated on October 8, 17, 24, and November 26 at which time the project was concluded.

Aqueous phase measurements of photosynthesis were made in the laboratory using the methods of Walker (1987) with the Hansatech DW2/2 (Hansatech, Inc., UK) oxygen electrode and a 2.5 ml chamber.

Effect of the explosion on biomass: Individual species

Chara zelandica lost an average of 18.06% of its biomass over all distances. The greatest loss was seen at 6.5 m (24.3%) and the least at 2.5 m (15.5%) for blast 1. The greatest loss of biomass for blast 2 occurred at 6.5 m (19.3%) and the least at 2.5 m (10.3%). Plants for blast 1 had survival at 6.5 m, 8.5 m and lO.5 m. Plant survival for blast 2 was seen only at 4.5 m. No surviving plants regained 100% of their original biomass while the control plants had 109% of their original biomass at the end of the project, a net gain of 9.3%.

Ludwigia peploides gained biomass in some instances, as high as 5.3% for blast 2 at 4.5 m. Biomass losses ranged from 10.7% at 4.5 m and less than 1% at 8.5 m for blast 1. Blast 2 losses were seen only at 4.5 m (1.5%). Plants at 2.5 m for blast 1 were the only group of L. peploides to have 100% mortality. The surviving test plants had a greater increase in biomass than the control plants, which gained only 1.7%; however, none of the surviving plants regained 100% of their original biomass.

Myriophyllum heterophyllum lost biomass in both test blasts. Blast 1 had the greatest loss at 2.5 m (24.3%) and the least at 4.5 m (<1%). Greatest loss of biomass for blast 2 was also at 2.5 m (19.3%) and the least at 4.5 m (1.5%). Mortality was 100% for both test shots at 2.5 m, 4.5 m and 6.5 m. Mortality was also 100% in blast 1 at 8.5 m. None of the surviving test groups regained 100% of their original biomass. The control group had a net gain of 17.9% for both tests. Plants at 4.5 m for blast 2 had a small gain in biomass (3.2%) after the test. Biomass loss for blast l ranged from 13.2% (6.5 m) to 8.6% (4.5 m). Biomass losses for blast 2 ranged from 23.9% (10.5 m) to 8.9% (6.5 m). Growth curves for all test groups became positive after the second week. The control group had a net gain of 19.9% over its original biomass by the end of the study. Five of the ten test groups had greater biomass than before the test. The group at 2.5 m in blast 1 gained more biomass than the control (39.4%).

Nitella acuminata lost biomass in all test groups as a result of the explosion. Losses for blast 1 ranged from 9.6 (10.5 m) to 5. 5% (8.5 m), while blast 2 ranged from 14.0% (2.5 m) to 2. 8% (6.5 m). All plants at 2.5 m for both test blasts and at 4.5 m for test 2 had 100% mortality. The control group had 26.2% greater biomass at the end of the project. For blast 1, groups at 87.5 m and 10.5 m had greater biomass than their original biomass. Biomass for test 2 was greater at 8.5 m than originally, although other surviving groups had greater than 95% of their original biomass.

Effect of the explosion on photosynthetic rates

All species responded to the explosion in a similar manner, i.e., a reduction in photosynthetic rate in the treatment group of plants, relative to the control. The effect on photosynthesis was greatest nearest the blast (2.5 m), and became progressively less severe with each increment in distance (4.5 m, 6.5 m, 8.5 m, and 10.5 m). Two species, N. acuminata and C. contraria, maintained positive, but low, rates of photosynthesis at 2.5 m. At 4.5 m, M. heterophyllum began to show photosynthetic activity, followed by C. zelandica at 6.5 m. By 8.5 m, all species demonstrated photosynthetic activity. As a percent of the photosynthetic rate of the Control the species ranked as follows:

2.5 m, NA > CC > MH=LP=CZ;

4.5 m, NA > MH > CC > LP=CA;

6.5 m, NA > MH > CC > CZ> LP;

8.5 m, NA > MH > CC > CZ> LP;

10.5 m, NH=NA > CC > CZ > LP.

These results are preliminary and are currently being prepared for publication. Work is currently in progress to establish the relationship between pressure waveform and plant damage and mortality.

MITIGATION TECHNIQUES TO PROTECT AQUATIC PLANTS FROM UNDERWATER EXPLOSIONS

Mitigation techniques described for fish are also applicable to aquatic plants (see Chapter 8). Any attempt to reduce the pressure waveforms will reduce the potential kill zone of aquatic plants.

CHAPTER 4

THE ENVIRONMENTAL EFFECTS OF UNDERWATER EXPLOSIONS: AQUATIC INVERTEBRATES

INTRODUCTION

The potential for injury and mortality to aquatic invertebrates, resulting from underwater blasts, has been well documented in agency and contractor reports and the scientific literature. However, with the exception of brief literature reviews concerning the effects of seismic exploration (Alperin 1967, Linton et al. 1985b) and ordnance testing (O'Keeffe and Young 1984), a comprehensive critical review of the literature does not exist.

The purpose of this review is to provide a comprehensive description of the experimental designs for each reported investigation. The study design aspects reviewed are: species tested, how organisms were caged, type and weight of the explosive charge, location of the explosive charge and test organisms in the water column, duration of the mortality test, pressure wave recording techniques and author's conclusions. This review also provides a critical evaluation of the studies based on their experimental designs and analysis of data.

APPROACH

Existing literature was reviewed in chronological order based on publication date. This approach was taken rather than a phylogenetic analysis in order to best evaluate study results for each investigation based on their experimental design. In addition, inadequacies in study design (e.g., small sample size, inadequate or no controls, differences in post-explosion mortality observation periods, and differences in cage material) make comparison among studies difficult, if not impossible. All of the studies, with the exception of Linton et al. (1985a), were originally designed and conducted using English measurements. To maintain the integrity of the original studies, all data are reported in English measurements and followed with metric equivalents in parentheses. Conversions were rounded to one decimal place. Metric conversions have been made to reproduce the English unit; added significant digits of the metric conversions do not represent the precision of the original research.

Common and scientific names follow Cairns et al. (1991) for Cnidaria, Turgeon et al. (1988) for mollusks, and Williams et al. (1989) for decapod crustaceans. Common and scientific names not covered in American Fisheries Society publications are used as given in the original publication. In some instances, either the common or scientific name of the organism being tested was given in the original publication, but not both. In such cases the appropriate common/scientific name has been provided in parentheses with an equal sign to indicate that the name has been added and was not part of the original publication.

INVERTEBRATE LITERATURE REVIEW

The first published investigation of invertebrate mortality resulting from underwater explosions was conducted by Knight (1907) in response to a "doleful tale of a poor lobster fisherman" related to Knight by a young seaman. The young seaman's story was that "when the lobster fisherman had accumulated about 500 animals in his pound (a pound is a cubical box made of wooden slats, anchored from shore, which allows water to pass through), some mischievous or ignorant person put off a dynamite blast about 150 or 200 yd (137.2 or 182.9 m) away, and killed every

lobster." As the young seaman first told the tale, "the lobster pound was 500 yards [457.2 m] away, but on cross-examination he was compelled to reduce the distance."

To test the accuracy of this story, six lobsters (=American lobster, Homarus americanus) were obtained from a local fisherman and tested with varying charge sizes and distances from the blast in water 12 to 15 ft (3.7 to 4.6 m) deep. In the first experiment, 3 large sticks of dynamite (of undefined weight) were detonated at a distance of 80 ft (24.4 m) from a lobster trap containing 2 lobsters, and at a distance of 40 ft (12.2 m) from a small lobster that was tethered by a piece of twine. The explosion produced no effect upon any of the lobsters.

In a second experiment, 2 large sticks of dynamite (of undefined weight) were exploded at a distance of 20 ft (6.1 m) from the small lobster. The animal was uninjured. The third experiment consisted of detonation of two sticks of dynamite within 10 ft (3.0 m) of a medium sized lobster. Knight (1907) indicated that there was "No result." In the last experiment, 3 sticks (of undefined weight) were exploded 15 ft (4.6 m) away from a trap which contained 5 lobsters which had all been used in previous experiments. The explosion overturned the trap, nearly overturned one of the piles on which the wharf was built, but "it seemed to have no effect on the lobsters."

Knight (1907) concluded that the 500 lobsters of the sailor's yarn had died, not from the effects of a dynamite explosion, but from suffocation. He surmised that the lobsters had been confined in too small a pound for too long a period, and the explosion was coincident with the fisherman's discovery of the dead lobsters.

The next published series of experiments evaluating the effects of explosives on invertebrate mortality occurred in response to a request from the Magnolia Petroleum Company to utilize dynamite charges up to 800 lb (362.9 kg) during the course of a refraction seismograph survey in waters off the coast of Louisiana. The area involved was in the heart of Louisiana's "jumbo" shrimp fishing grounds. Descriptions of the study design and results are presented in various degrees of detail in five separate non-refereed publications (Gowanloch and McDougall 1944, 1945, 1946; Gowanloch 1946a, 1950)

The first series of experiments, best described in Gowanloch and McDougall (1945), involved the firing of one 200 lb (90.7 kg) and two 800 lb (362.9 kg) charges of 60 percent gelatin dynamite unconfined and placed on the sea bottom in 18 ft (5.5 m) of water. Forty-five shrimp (Peneus setiferus) and thirty oysters (Ostrea virginica) were placed in 30 inch (762 mm) cubicle cages, positioned at 50, 100, 150, 200, 300, and 400 ft (15.2, 30.5, 45.7, 61.0, 91.4 and 121.9 m) from the shot point, and suspended midway between the surface and bottom in 18 ft (5.5 m) of water. Test animal were held in their positions for 48 hours before the charges were fired, were examined immediately before the shot, immediately after the shot, and at 24 and 48 hours post detonation exposure. Gowanloch and McDougall (1946) state that "adequate controls were established located far beyond any possible influence from the dynamite blasts." However, no details are given concerning control handling or subsequent mortality. Geophones, located at selected cages, recorded "the amplitudes of each charge." However, no pressure data were presented.

Gowanloch and McDougall (1945) concluded that shrimp were uninjured at 50 ft (15.2 m) by the 800 lb (362.9 kg) charge. They noted that "the shrimp still remained normal six days after the explosion. Yet the shock shook an oyster tugger ten miles away, and threw water 300 ft [91.4 m] into the air." They concluded that "No differential mortality could be found among the oysters, but for various biological reasons the authors consider that more experimental work is necessary before a satisfactory definite decision can be reached." No statistical basis for their conclusions or supporting data in tabular form are given on which statistical analysis could be conducted by the present authors.

A second series of experiments was conducted, "Since oysters constitute a highly valuable aquatic resource, damage to which was not apparent, when the experimental oysters were suspended as individuals in cages it was decided to re-examine effects of dynamite blasting on oysters where the oysters were part of an integrated reef" (Gowanloch and McDougall 1946). Descriptions of the study design and results are again presented in various degrees of detail in four separate non-refereed publications (Gowanloch and McDougall 1946; Gowanloch 1946b, 1948, 1950). It was concluded that the "seismographic explosions caused no subsequent mortality to the oysters."

Gowanloch and McDougall (1945) used cages that were 30 in (760 mm) cubes, constructed with a strong external wooden slatted frame (picture of cage on page 303 of Gowanloch (1948)). Specimen confinement was accomplished by attaching 1/2 in (13 mm) shrimp netting to the inside of the frame. Each cage was divided into two compartments by a vertical wall of shrimp netting. Anonymous (1948) questioned Gowanloch and McDougall's (1945) results since slatted wooden cages had been used in their experiments. Anonymous (1948) contended that use of the slatted wooden cages would "tend to produce a decrement in the shock and pressure reaching the enclosed animals." In addition, Aplin (1947) noted that during experiments previously conducted in Louisiana (presumably by Gowanloch and McDougall) "it was found wooden cages would be broken up by the explosions unless so heavily built as to give the impounded fish definite protection from the shock." Neither Anonymous (1948) nor Aplin (1947) provided experimental support for their contention.

Linton et al. (1985b) make reference, in their annotated bibliography, to a paper by Gowanloch and McDougall published in <u>Louisiana Conservationist</u> 4(12):13-16. The publication date, title, volume, and page numbers are identical to Gowanloch and McDougall (1945) published in <u>Oil</u>. A check of the <u>Louisiana Conservationist</u> indicates that this article does not exist.

Aplin (1947) conducted a series of experiments to determine the effects of explosives used in geophysical survey work to locate oil deposits along the California Coast. Four rough abalones (<u>Haliotis</u> <u>corrugata</u>) and four green abalones (<u>Haliotis</u> <u>fulgens</u>) were exposed to a 20 lb (9.1 kg) charge of 60 percent petrogel, fired 4 ft (1.2 m) below the surface. The abalone were on the bottom, 55 ft (16.8 m) from the explosion. An hour after exposure the abalones were able to move when given tactile stimulation. However, none of them extended their mantles when put into an aquarium and all were dead within a few hours. Aplin (1947) noted "that further experiments will have to be made as they may have been killed by handling and transportation."

Aplin (1947) exposed eight lobsters (<u>Panulirus</u> <u>interruptus</u>) 270 to 300 mm long to a 20 lb (9.1 kg) charge of 60 percent petrogel, fired 4 ft (1.2 m) below the surface. The lobsters were on the bottom, 55 ft (16.8 m) from the shot and almost directly below it. Five hours post exposure the lobsters were all alive and active. In a second test shot, 13 lobsters ranging from 170 to 230 mm in length were exposed to a 20 lb (9.1 kg) charge of 60 percent petrogel, fired 4 ft (1.2 m) below the surface. The lobsters were positioned 4 ft (1.2 m) below the surface and 50 ft (15.2m) away from the shot. Three hours post exposure the test lobsters were alive and examination of internal organs found no signs of damage. Aplin (1947) concluded that "Apparently lobsters are very resistant to concussion..." Aplin, as with his abalone test, did not use controls. However, since there was no mortality in the test lobsters it can be assumed that those factors which would be controlled for (i.e., handling, transportation, and water quality) did not cause mortality.

Both the abalone and lobster studies suffer from serious experimental design flaws including extremely small sample sizes, no replicate tests, and complete lack of controls. No description of how the abalones and lobsters were caged is provided in the text; although, fish were held in 3 ft (910 mm) square and 18 in (460 mm) deep

cages made of welded iron frames covered with 1/2-in (13 mm) mesh wire hardware cloth. Because of the small sample sizes and lack of controls, no conclusions can be made from this study.

Anonymous (1948, pp. 16-18) conducted a series of tests utilizing oysters (=eastern oyster) (Ostrea virginica) held in wire bags placed on the bottom. Table 4.1 provides data on two tests conducted with the largest explosive charge, 300 lb (136.1 kg) of TNT. They concluded that "Deaths among these over the two-week period all occurred within the 200 ft (61.0 m) radius except for a single dead oyster found in a bag exposed at a distance of about 960 ft (292.6 m). Excluding this one, it was found that the two week's loss was 5.4%, or a little more than double that observed immediately after the explosion." No attempt was made to measure explosive pressure waves during mortality testing. No statistical analysis of the data was conducted by the authors.

An analysis of the oyster data provided in Anonymous (1948) using a Cochran-Armitage Trend Test on a 2 X C stratified contingency table (strata = shot) were not significant (P>0.2) for distances to 960 or 400 ft (292.6 or 121.9 m) from the blast. It is concluded that the relatively low numbers of dead oysters did not change with distance from the blast. Furthermore, some mortality occurred in the controls and it is likely that some oysters dying at 2 or 16 weeks died from causes not related to the blast.

Table 4.1- Immediate, 2-week and 6-week live/dead counts for oysters (=eastern oyster, Ostrea Virginica) placed on bottom at 30 ft (9.1 m) depth and exposed to a 300 lb (136.1 kg) charge of TNT suspended 15 ft (4.6 m) (From Anonymous 1948).

SHOT 16

Distance from Explosion		Initial Observation 10-5-1945		2 Week Observation 10-18-45		6 Week Observation 11-16-45	
Feet	Meters	Live	Dead	Live	Dead	Live	Dead
25	7.6	19	1	17	2	15	2
50	15.2	19	0	16	3	13	3
100	30.5	23	1	21	2	19	2
200	61.0	20	0	19	1	18	1
400	121.9	20	0	20	0	18	2
960	292.6	20	0	19	1	16	3
Control		20	0	20	0	Lost	

SHOT 17

Distance from Explosion		Initial Observation 10-6-1945		2 Week Observation 10-19-45		6 Week Observation 11-17-45	
Feet	Meters	Live	Dead	Live	Dead	Live	Dead
25	7.6	21	0	21	0	20	1
50	15.2	23	1	22	1	22	0
100	30.5	26	0	25	1	23	2
200	61.0	29	1	29	0	25	4
400	121.9	26	0	26	0	21	5
Control	292.6	30	0	30	0	27	3

Anonymous (1948) conducted a series of tests utilizing blue crabs (Callinectes sapidus). They provided data, shown in Table 4.2, that summarizes four tests where blue crabs were held in cages placed on the bottom (depth not given) and exposed to

a 30 lb (13.5 kg) charge of TNT. Based on the results presented in Table 4.2, Anonymous (1948) noted that about 90% of the blue crabs were killed at 25 ft (7.6 m), under peak pressures exceeding 800-900 pounds/square inch, psi (5,516-6,206 kPa), and very few died at 150 ft (45.7 m), where pressure reached about 270 psi (1,862 kPa). Anonymous (1948) noted that intermediate distance gave surprising results, marked by the absence of any trend. This was confirmed by the present authors, utilizing a chi-square test. However, first value, and last value, differ from intervening four values ($P<0.001$), and first and last values differ ($P<0.001$). The second and third values do not differ ($P>0.1$), and values (2, 4, and 5) versus value (3) has $P=0.05$. Anonymous (1948) suggested that the erratic variation may be due to the irregular transmission of the shock wave along the bottom or to other unestablished causes. Although, external and internal damages were not quantified, they observed loss of part or all of the carapace, cracking of the carapace, heart rupture, broken spines and, autonomous loss of one or both claws. However, many of the crabs killed showed no macroscopic changes. Anonymous (1948) provided no data for control mortality, nor did they indicate that controls were used. Although the true mortality levels due to the blast cannot be known exactly, the data at 150 ft (45.7 m) give an upper bound of 7% on the "control" (e.g., handling) mortality.

No discussion is provided describing pressure recording. It is not clear if pressures were recorded specifically for this set of four experiments or if they used generic pressures given in Figure 7. This is an important point since pressure readings may vary with depth of charge, depth of pressure gauges and nearness of gauges to either the water-air (surface) interface or water-substrate (bottom) interface. In addition, Anonymous (1948) used copper ball crusher gages, which only record peak pressure.

The authors provide no information on how long crabs were held prior to determining mortality (i.e., instantaneous, 24 hr. 48 hr. or 96 hr. mortality). Period of observation could easily affect mortality levels, with longer periods having higher mortality, especially with no controls to evaluate the effect of holding time.

Table 4.2- Effect of 30 lb (13.5 kg) charges of TNT on blue crabs (Callinectes sapidus) held in cages on the bottom (bottom depth not given). Summary of four tests (From Anonymous 1948).

Distance from charge		No. held	% killed	% surviving
Feet	Meters			
25	7.6	37	89%	11%
50	15.2	55	38%	62%
75	22.9	22	55%	45%
100	30.5	37	38%	62%
125	38.1	23	48%	52%
150	45.7	14	7%	93%

Tollefson and Marriage (1949) evaluated the effects of channel blasting on three species miscellaneous crab species (Cancer sp.), and Pacific oysters (Ostera gigis). Cockles were captured the week prior to testing and held in an aquarium. They ranged in size from 60 to 79 mm rib length, average 70 mm. Oysters were clusters, ranging from 4-12, average 8.4 per cluster, of one and two year old taken from adjacent beds. Crabs used were small miscellaneous specimens brought from the Newport laboratory where they had been held for several months or more. They ranged in back width from 115 to 144 mm, average width 129 mm.

All specimens, except oysters, which were placed at 20 ft (6.1 m) or less from the center of the blast were placed in separate canvas sample bags with labels to facilitate locating and to prevent any mixing of specimens following the blast. It

is not clear how oysters and organisms beyond 20 ft (6.1 m) were handled. Tollefson and Marriage (1949) noted that they did not believe the canvas bags would affect the results. No control organisms were used. Four cases of 50 percent dynamite were fired as a single shot along a 95 ft (29.0 m) line in a sandy mud bottom intertidal area at Bayocean, Oregon. The mean depth of planting of dynamite was about 3 ft (0.9 m) below the surface. Water depth was 1 to 3 ft (0.3 to 0.9 m). No pressure measurements were taken.

Tollefson and Marriage (1949) found that a number of miscellaneous organisms, crabs (Cancer magister), a small snail (Thais Ep.), a small mud clam (Macoma sp.), and a single specimen of a commensal clam (Pseudopythina rugifera), were unaffected, while three sand worms (Nereis sp.) and several ribbon worms (Nemertinea) were found dead within 25 ft (7.6 m) of the blast. A number of ghost shrimp were found within 25 ft (7.6 m) of the blast. Seven of nine Callianassa sp. and 39 of 76 Upogebia pugettensis were found dead or died within 24 hours of the blast. The authors concluded:

1. "Little or no damage to surface cockles located 10 ft [3.0 m] or further from the center.

2. No damage to sub-surface cockles located 15 ft [4.6 m] or further from the center.

3. No damage to crabs located 30 ft [9.1 m] or further from the center.

4. No damage to oysters located 10 ft [3.0 m] or further from the center. (The foregoing does not consider any possible after-effects such as silting.)

5. A 50 to 75 percent mortality of ghost shrimp was found within 25 ft [7.6 m] of the center.

6. In the case of the invertebrates involved it is likely that almost all damage done by blasting is grossly physical in nature, that there is little shock or other after effects."

This study suffers from a number of serious design flaws and omissions of methodology information. Sample sizes were extremely small. There were no control animals. No information is provided on total weight of explosive detonated, other than "four cases" were exploded. A typical case of dynamite contains 50 lb (22.5 kg) of explosives; however, the strength and size of each cartridge causes the weight of each "stick" to have considerable variation. No information is provided on the canvas sample bags. Contrary to the authors' statement that the bags would not have "exerted any appreciable cushioning effect", the bags could have reduced pressure wave transmission and thereby reduced mortality levels. In addition, no information is provided on how test organisms were held beyond 20 ft (6.1 m). Pressure wave measurements were not made. The lack of explosive weight data, use of a linear charge pattern, and burial of the explosive, make prediction of explosive pressures using existing empirical relationships, for example Cole (1948), impossible. As such, it is impossible to determine the magnitude of pressure experienced by the organisms. Thus, the results are, at best, lower trend estimates of the mortality that unconfined organisms would experience.

Fry and Cox (1953) made casual observations on the effects of black powder on invertebrates off the coast of California during seismic exploration activities. The major objective of the study was to determine if fish were being killed by seismic exploration charges. A 45 lb (20.4 kg) charge of E.P. 138 Seismograph Black Powder was detonated within 6 ft (1.8 m) of the surface and divers were sent down

to make observations of damage. The authors noted that "Clams and tube worms were found, none of which had suffered ill effects from the blast. These animals all responded in the normal manner by quickly withdrawing siphons and tentacles when touched by the divers." After the second day of testing, the authors noted that "None of the invertebrates seemed to be affected; the sea anemones were extended, as were the tube worms; none of the corals had been broken; the sea urchins were still on the rocks and the sea cucumbers had not contracted."

Fry and Cox (1953) gave no information concerning the distance of the explosion from the invertebrates being observed by the divers. As such, it is impossible to even conclude that the invertebrates were unaffected at a given distance from a known size explosion.

It is quite possible that Fry and Cox's (1953) observations are related to the type of explosive utilized. It had been previously observed that black powder, a combusting medium and not an explosive, has little effect on fish (Baldwin 1954; Fry and Cox 1953; Ferguson 1962; Hubbs and Rechnitzer 1952) when compared to high explosives such as dynamite. For example, Hubbs and Rechnitzer (1952) found that in marine fish species tested, the lethal threshold peak pressure from dynamite explosions varied from 276 to 483 kPa. Peak pressures from slowly detonating black powder, producing pressures as high as 855 to 1,103 kPa, did not kill caged fishes. The difference in fish mortality between black powder, a low explosive, and high explosives appears to be related to the waveform produced by each explosive type. Black powder produces a pressure waveform with a slow rise time and low amplitude whereas high explosives have an abrupt rise time, high amplitude, and short frequency. In addition, high explosives have a much higher negative pressure than black powder, as shown in Figures 8 and 9 in Hubbs and Rechnltzer (1952). The amplitude and short frequency of the negative pressure wave and resulting damage to the swim bladder may be the causative factor of mortality in fish exposed to high-explosive pressure waveforms.

Sieling (1954) conducted two experiments, carried out in separate locations during 1949-1950, to evaluate the effects of seismic exploration for oil on oysters in the Barataria Bay, Louisiana, region. Work in Bay de Chene was referred to as Experiment 1 and Bay Batiste work was referred to as Experiment 2.

Two explosive charges were used in each shot hole, one of 50 lb (22.7 kg) and one of 20 lb (9.1 kg) of Nitranon (nitro-carbonitrate), and these were exploded at a depth of 50 ft (15 2 m) and 30 ft (9.1 m) respectively. Charges were placed in pipes which were in holes drilled into the bottom. The general procedure was to drill the hole from a drilling barge, then move to the next location. A barge carrying shooting equipment and explosive would then move in and load the first charge into the pipe and fire it, then as quickly as was safe load the second charge in the pipe and fire that. The two pieces of equipment would then move around the other four shot holes and fire the charges at each hole in the same manner.

Shot points formed a diamond with the points 1,000 ft (304.8 m) apart and one shot point in the middle. Sieling (1954) noted that this distance simulated the worst operating conditions possible under the law as when two lines of seismographic explosions cross at right angles. There was no attempt to measure pressures.

Oysters (=eastern oyster, _Ostrea_ _virainica_) were placed at 20, 60, 130 and 250 ft (6.1, 18.3, 39.6 and 76.2 m) from the point of explosions and in a staggered line. Control stations were located 750 ft (228.6 m) from the nearest shot point. At both the experimental and control stations oysters were put in trays and placed on racks above the bottom in Experiment 1 and placed on the bottom in Experiment 2. Water depth was not given. Additional controls, which are not described here, were established to evaluate the influence of various other environmental factors.

Results of this study are presented in Table 4.3. Sieling (1954) concluded that there was no correlation between the distance of the oysters from the explosions and the survival rate.

Kemp (1956) evaluated the effects of seismograph explosions by conducting a series of three tests with fish, shrimp (=Penaeus sp., three possible species occur in the area), oysters (=eastern oyster, Crassostrea virginica) and blue crab (=Callinectes sapidus) under actual exploration conditions. Test 1 was conducted in Corpus Christi Bay in water 13 ft (4.0 m) deep with a bottom of very soft, gray, mud. Test 2 was also conducted in Corpus Christi Bay in water 2 1/2 to 3 ft (0.8 to 0.9 m) deep with a bottom of hard sand. Test 3 was conducted in Aransas Bay in water 7 ft (2.1 m) deep with a bottom of soft, gray mud.

Specimens were held in 1/2 in (13 mm) mesh hardware cloth cages, except oysters which were in heavy wire trays. In each test one set of specimens was placed at the shot hole and 25, 50, 100 and 200 ft (7.6, 15.2, 30.5 and 61.0 m) from the shot hole. A set was also placed 1/4 to 1/2 mile (0.4 to 0.8 km) away as a control. Organisms were held on the bottom in all tests reported here. In test 1, organisms were also suspended 3 ft (0.9 m) below the surface; however, numbers were so small and at sporadic distances from the blast, that results are not presented here.

Test organisms were exposed to a 40 lb (18.1 kg) charge of Nitramon, the maximum allowed by law, at a depth of 20 ft (6.1 m) below the bay bottom, which is the minimum depth allowed. Charge weight and burial depth were the worst possible conditions permissible under the law. Pressure waves were not measured.

Kemp (1956) provides no indication of the waiting time period used prior to making live-dead counts. The results are shown in Table 4.4.

Table 4.3- Percent survival of oysters (=eastern oyster, Ostrea virginica) at Bay de Cene (Experiment 1) and Bay Bastiste (Experiment 2). Two explosive charges were used in each shot hole (see text for description of shot design), one of 50 lb (22.7 kg) and one of 20 lb (9.1 kg) of Nitranon (nitro-carbonitrate), and these were exploded at a depth of 50 ft (15.2 m) and 30 ft (9.1 m) respectively. Oysters were on the bottom (depth not given) (Modified from Seiling 1954, Tables 1 and 2).

Distance from Explosion	Number Tested	Number Surviving 4 Months	Percent Survival 4 Months	Number Surviving 7.5 Months	Percent Survival 7.5 Months
Experiment 1 - Bay de Chene					
Feet Meters					
20 6.1	345	289	83.7	---	---
60 18.3	348	302	86.7	---	---
130 39.6	336	287	85.3	---	---
250 76.2	333	281	84.4	---	---
Control	338 257		76.0	---	---
Experiment 2 - Bay Batiste					
Feet Meters					
20 6.1	334	275 82.3		253 75.7	
60 18.3	326	269 82.4		256 78.5	
130 39.6	324	281 86.8		255 78.7	
250 76.2	329	280 85.1		242 73.5	
Control	341	294 86.2		264 77.4	

Table 4.4- Live-Dead counts for shrimp (=Penaeus sp., three possible species occur in the area), oysters (=eastern oyster, Crassostrea virginica), and blue crab (Callinectes sapidus) in cages placed on the bottom of Corpus Christi Bay, TX and exposed to a 40 lb (18.1 kg) charge of nitramon buried 20 ft (6.1 m) below the bay bottom. For shot 1, organisms were in 13 ft (4 m) of water, bottom type was very soft gray mud. For shot 2, organisms were in 2 1/2 to 3 ft (0.8-0.9 m) of water depth, bottom type was hard sand (Modified from Tables 1 and 2 in Kemp (1956)).

SHOT 1

Distance		Shrimp		Oysters		Blue Crab	
Feet	Meters	Live	Dead	Live	Dead	Live	Dead
<5	<1.5	25	0	18	7	2	0
25	7.6	25	0	34	4	2	0
50	15.2	25	0	30	1	2	0
100	30.5	25	0	25	1	2	0
200	61.0	25	0	24	1	2	2
Control		25	0	32	0	2	0
<5	<1.5	25	0	37	4	1	0
25	7.6	24	1	41	1	1	0
50	15.2	25	0	38	1	1	0
100	30.5	25	0	47	0	1	0
200	61.0	25	0	38	0	1	0
Control		No control due to boat mechanical problems					

Kemp (1956) concluded that shrimp and crabs were "found to be completely immune to underwater explosions, since they suffered no ill effects whatsoever during the tests." The sample sizes for shrimp and crabs are adequate but they are too small to accurately estimate mortality. However, from the data provided, the upper 95% bound on the shrimp mortality at a given distance is 0.06 (n=50 by pooling both shots) to 0.11 (n=25 for individual shots). For blue crab the upper 95% bounds are 0.95 (n=1) and 0.78 (n=2). Pooling the data for both shots, the upper 95% bound on blue crab mortality is 0.63 (n=3) at distances 550 ft (167.6 m). The data suggest that the death of 2/2 blue crabs in shot 1 is an artifact and does not represent the effects of the blast. Pooling the data from both shots at ≤ 50 ft (15.2 m), the upper bound is 0.28 (n=9). Kemp noted that damage to oysters was most severe within a 25 ft (7.6 m) radius of the blast and some oysters were found as far as 200 ft (61.0 m). Based on these results he concluded "If the minimum distance (from the shot) from an oyster reef were extended from 300 to 500 ft (91.4 to 152.4 m), it would probably afford a more comfortable safety margin." Statistical analysis supports this conclusion. Pooling the data at 200 ft (61.0 m), the mortality is 1/62 = 0.016 + 0.016. For shot 1, the mortality is 1/24 = 0.042 + 0.040. For shot 2, the upper 95% bound on the proportion (12/38) is 0.075.

Anonymous (1962) conducted a series of tests with Dungeness crabs (=Cancer magister) to evaluate the effects of underwater explosions from oil seismic exploration. Tests were conducted off the Oregon coast north of the Alsea River in an area normally fished for crabs. Small crabs, less than 80 mm maximum carapace width, were caught in tide pools six weeks previous to testing. Adult crabs, over 130 mm minimum carapace width, were caught in commercial crab pots in Yaquina Bay a few days prior to the experiments. All were held in live tanks. Commercial crab pots were used as cages (12 test and 3 control). Eight crabs were placed in each of 14 pots -3 large hard shell, 3 large soft shell, and 2 small soft shell to a pot. A similar assortment was used for the remaining pot, excluding 1 large soft shell. Small crabs were placed inside a hardware cloth box, 6 x 6 x 12 in (150 x 150 x 305 mm) dimensions. Chelae of all crabs were tied with rubber bands prior to placement

in pots.

Two series of tests were conducted. In the first series, one 5 lb (2.3 kg) charge of nitro-carbonitrate suspended 2 ft (0.6 m) beneath the surface was fired between two crab pots placed about 50 ft (15.2 m) apart on the bottom at each of two depths, 8 and 15 fathoms (14.6 and 27.4 m). A 25 lb (11.3 kg) charge was exploded at a depth of 4 ft (1.2 m) over two additional pots similarly spaced in 35 fathoms (64.0 m) of water. In the second series, equivalent size charges and number of pots were used. All other conditions were similar to the first experiment except that the charges were detonated 20 ft (6.1 m) beneath the surface in the 8 and 15 fathom (14.6 and 27.4 m) depths and 40 ft (12.2 m) in the 35 fathom (64.0 m) depth. Pressure measurements were not made.

One pot was recovered and crabs were examined at each depth in both series within 30 min after the explosion. The remaining pots were recovered at 96 hr. Divers examined the condition of crabs on the bottom and at the 8 and 15 fathom (14.6 and 27.4 m) depths of both series prior to recovery immediately following the blasts.

Three of 15 pots were placed on the bottom in the study area and retrieved at 96 hr. After the blast one pot was placed about 100 ft (30.5 m) from the remaining test pot at each depth in the first series.

The results for all charge sizes, cage depths, carapice condition (soft or hard), and crab sizes tested are combined and summarized in Table 4.5. Totals of 37 live undamaged and 11 dead or damaged (including 3 live) crabs were observed in test pots recovered immediately after the explosions. The test pots recovered at 96 hr contained 31 live undamaged and 16 dead or damaged (including 5 live) crabs. The control pots, examined at 96 hr. contained 16 live undamaged and 8 dead or damaged (including 2 live) crabs. No small crabs were found dead or damaged in any group. A Kruskal-Wallace test, utilizing data in Table 4.5, on a singly ordered r x c (treatment+day x response, where for response = alive, injured, dead) was not significant (P>0.4). Anonymous (1962) concluded the following:

1. There was no significant difference in the mortalities or damage between the test and control groups.

2. There was no significant difference in mortalities or damage with the crab pots placed at different depths.

3. There was no significant difference in numbers of mortalities or damage between surface and submerged shots.

4. There was no significant difference in numbers of crabs dead or damaged between 5 and 25 lb (2.3 and 11.3 kg) charges.

Brown and Smith (1972) evaluated the effects on marine life of three charges, 40 to 60, 400 and 2,170 lb (18.1 to 27.2, 181.4 and 984.3 kg) of C-4, used to clear a beach area and create a boat lane on in a cove at Cross Cay, a small island located east of Roosevelt Roads, Puerto Rico.

Table 4.5- Blast related mortality and injury of Dungeness crabs (=Cancer magister). The results for all charge sizes, cage depths, carapice condition (soft or hard), and crab sizes tested are combined and summarized. A Kruskal-Wallace test, utilizing the combined data, on a singly ordered r x c (treatment+day x response, where for response = alive, injured, dead) was not significant (P>0.4) (Modified from Anonymous 1962, Table 5, page 12).

Aliv	e	Injured	Dead	Total
Day 0 Treatment	37 (77.08 %)	3 (6.25 %)	8 (16.67 %)	48 (100 %)
Day 4 Treatment	31 (65.96 %)	5 (10.64 %)	11 (23.40 %)	47 (100 %)
Day 4 Control	16 (66.67 %)	3 (12.50 %)	5 (20.83 %)	24 (100 %)

A single large snail (conch type) and a sea urchin (Lytechinus sp.) were placed in one of three cages containing fish. Pressure measurements were taken at three locations for the largest shot. Casual observations of the cove were made after the explosion.

Neither the caged snail or sea urchin were killed by the blast. However, the hydrophone nearest the cage was apparently defective so no pressures were measured for these two animals. Two hours after the last explosion, turbidity in the cove had cleared sufficiently for an in-water survey. Live sea urchins and chitons were observed. Almost all of the staghorn coral (Acropora palmata) colonies were broken off near their bases and encrusting coral (Millepora complanta) appeared to have suffered some abrasion.

Small sample sizes, lack of adequate pressure readings, and lack of information concerning charge distance from the staghorn coral and encrusting coral make it impossible to form any quantitative conclusions from this observational study. However, the original authors concluded: "...[B]ased on the results of the experiment and the observations of the environmental effects of the explosions, it is felt that the proper precautions were taken to keep the damage to the environment to a minimum." Considering the study and report production costs, the present authors question why this poorly designed study was conducted.

Gaspin (1975) and Gaspin et al. (1976) conducted a series of tests using blue crabs (Callinectes sapidus) and eastern oysters (Crassostrea virginica) to investigate the effects of naval ordnance testing in Chesapeake Bay.

In 1973, explosive effects were conducted (Gaspin 1975). Test animals were collected in the Patuxent River in the vicinity of Solomons Island. Crabs were collected in the Patuxent River with a 25 ft (7.6 m) semiballoon otter trawl with a 1/2 in (13 mm) stretch mesh liner. Oysters were collected with a 48 in (1.2 m) oyster dredge at an unspecified site. Organisms were held in cages until used. No information on holding time prior to testing was provided. Cages, constructed with plastic mesh fabric on steel frames, were cylinders 20 in (510.0 mm) long and 12 in (305.0 mm) in diameter. Organisms were placed in cages and positioned at a depth of 5 ft (1.5 m), referred to as surface cages, and on the bottom in 25 ft (7.6 m) of water, at horizontal standoff distances from the charge (Table 4.6). Crabs were placed in both the surface and bottom cages, while oysters were placed only on the bottom. Sample size was small and variable, ranging from 9-20 individuals per distance tested. There is no indication that controls were utilized.

The organisms were exposed to 200 lb (90.7 kg) Mk 82 general purpose bomb, placed on the bottom. Shot #532 was loaded with tritinol and shot #533 was loaded with H-6. The pressure wave was recorded. However, the gain on some of the recording

system channels was set too high and the records were clipped. As such, good pressure measurements were not made.

Crabs and oysters were examined for obvious external damage and those still alive after an explosion were held in flowing water for 24 hours to detect any delayed mortality. Results are given in Table 4.6. Gaspin (1975) stated "Little can be concluded... Some oysters and crabs were killed at stations nearest the explosions but many survived."

In 1975, (Gaspin et al. 1976) a single shallow water test was conducted in approximately 25 ft (7.6 m) of water in the Patuxent River. Test oysters (Callinectes sapidus) were collected with an oyster dredge in the vicinity of Solomons Island. Blue crabs (Ostrea virginica) were either captured by otter trawl and oyster dredge, or purchased. Organisms were placed in cages and positioned at a depth of 5 ft (1.5 m), referred to as surface cages, and on the bottom, at six horizontal standoffs from the charge. Crabs were placed in both the surface and bottom cages, while oysters were placed only on the bottom. A description of the cages was not provided. The organisms were exposed to a 106 lb (48.1 kg) spherical pentolite charge, placed on the bottom. Peak pressure measurements were recorded.

After exposure, crabs and oysters were examined for obvious external damage and then the test cages were immediately submerged in holding tanks, later to be transferred and held in wet tables at the Chesapeake Biological Laboratory. A small sample of test crabs was dissected and examined for internal damage, but all examinations were inconclusive and the procedure was later abandoned. With the exception of the severed muscle tissue and ruptured organs that resulted from massive fractures in the carapace, no internal damage was discernable.

Percentage of cumulative blue crab mortality for test distances and controls is presented in the original text as a figure (p. A4). However, total numbers of test and control organisms are not given in the text or figure. As such, it is impossible to determine if adequate sample sizes were employed. In addition, control mortality exceeded or closely approached exposure mortalities, which questions the usefulness of the results. Gaspin et al. (1976) noted that the high mortalities which occurred within the control groups might be (in part) attributable to the differences in handling between controls and test crabs. Due to space limitations within the holding tanks, the cages containing the controls were held out of water several hours longer than the control cages during transfer to the laboratory.

Table 4.6.-Blast related mortality of blue crabs (Callinectes sapidus) and eastern oysters (Crassostrea virginica). Charges erer 200 lb (90.7 kg) Mk 82 general purpose bombs. Shot 532 was loaded with tritinol and Shot 533 was loaded with H-6 (Modified from Gaspin 1975, Table A-1).

Species	Distance		Cage Depth		Pmax	Survival	Mortality
	Feet	Meters	Feet	Meters	(kPa)		
Shot 532							
crabs	50	15.2	25	7.6	1,679	7	2
	110	33.5	5	1.5	484	15	5
	110	33.5	25	7.6	1,264	10	0
oysters	50	15.2	25	7.6	1,679	10	0
	110	33.5	25	7.6	1,264	12	0
Shot 533							
crabs	40	12.2	25	7.6	1,600	11	1
	75	22.9	5	1.5	1,206	9	1
	75	22.9	25	7.6	1,637	7	3
oysters	40	12.2	25	7.6	1,600	6	7
	75	22.9	25	7.6	1,673	11	2

The only oyster mortality occurred at the 20 ft (6.1 m) bottom station. Twenty hours after the shot, 5 of 20 oysters were dead. Between 20 and 41 hours, one additional oyster died. There was no change after 140 hours, giving 6 of 20 dead (30% mortality). It was indicated that there were no other oyster mortalities in 140 hours of observation.

Gaspin et al. (1976) concluded: "The great resistance exhibited by the test oysters is, therefore, a good indication of the reaction that can be expected to occur in natural oyster populations. However, there is at least one problem with methodology. No indication of sample sizes at each exposure distance or control are given, other than 20 oysters were used at the 20 ft (6.1 m) location. During the 1974 testing program (Gaspin 1974), variable sample sizes ranging from 9 to 20 individuals were used for both crabs and oysters. As such, it is impossible to say that the sample size was 20 individuals for each exposure distance and control.

Linton et al. (1985a) conducted a test with both fish and invertebrates, with the intention of determining adequacy of regulations imposed by governmental agencies that permit geophysical exploration intended to minimize detrimental effects of geophysical exploration on marine organisms. American oysters (=eastern oyster) (Crassostrea virginica), white shrimp (Penaeus setiferus) and blue crab (Callinectes sapidus) were used as test invertebrates.

All test organisms were collected in Trinity Bay, north of Smith Point, Texas within one kilometer of the detonation site. Blue crabs were captured with commercial traps, oysters with a commercial dredge, and white shrimp with an otter trawl. Test organisms were selected for uniform size within species. Range and average were: white shrimp, 7-11, 85 mm total length; blue crab 14-18, 170 mm-carapace width. Oysters were not measured individually, but none was less than 150 mm in total shell length.

Crabs and oysters were transported in aerated tanks to open-water holding pens immediately after capture. They were held there for at least 24 hr prior to the experiment to monitor injuries and mortalities resulting from capture and handling. Shrimp were captured the day of the experiment and transferred directly to test cages. No attempt was made to determine shrimp mortality or injury resulting from

capture or handling. All organisms were acclimated to test-cage conditions for at least one hour prior to detonation.

During testing, organisms were held in cylindrical holding cages, 900 by 750 mm, and enclosed with 18 mm nylon mesh webbing. Cages holding shrimp also contained a 5 mm mesh liner. Ten crabs and 10 oysters were caged together. White shrimp were caged alone, 10 individuals per cage. Shrimp were held in paired cages at surface and bottom locations (4 cages per location), whereas crabs and crabs and oysters were only deployed in paired bottom cages.

Linton et al. (1985a) stated that surface and bottom cages were deployed at five stations arranged perpendicular to, and at logarithmic distances of 1, 11, 23, and 46 m from the detonation line. However, based on their Figure 2 (p. 345) showing the test array of cages, distances are from the explosive to the vertical line maintaining both surface and bottom cages. Actual or slant distances from the explosion to the surfaces cages would have been 24.0, 26.4, 33.2 and 51.9 m. Distances from explosion to bottom cages are as stated.

Bottom cages were deployed at 24 m depth and surface cages were floated at the surface. Controls were established at a distance of 136 m from the detonation site. Control organisms received the same treatment (that is, method of capture, and holding time as test organisms), with the exception that they were not in the water at the time of the explosion.

Test organisms were exposed to a 33 m strand of 100 g/33 cm Primacord detonation cord laid perpendicular to the transect of test cages. It was positioned to form the top of the letter "T" and the line of cages forming the base. Both Primacord ends were weighed to hold the cord on the bottom, 24 m depth. A blasting cap was used to initiate the detonation. No pressure measurements were made.

After the test, observers raised the cages and recorded mortality among test animals. Criteria used to denote death were: oysters-shell permanently agape; shrimp-cessation of gill movement; and crabs-cessation of movement of chela, appendages, and mouth parts. Dead organisms were removed from their cages. Cages with living organisms were returned to the position they occupied at the time of detonation and observed 24 hours later and separated as to living or dead.

The results are presented in Table 4.7. Surface cage distances are corrected from those presented in the original publication (Table 1, p. 346) to reflect actual distance from the explosion.

White shrimp exhibited no well-defined pattern relative to survival and distance from the detonation site (Table 4.7).

Without pressure wave measurements it is impossible to determine if cages received variable pressures that would explain the observed mortality pattern.

Blue crab mortality, immediately following the blast, ranged from 40 percent at 1 m to 10 percent at 47 m. Twenty-four hour mortality ranged from 60 percent at 1 m to 10 percent at 47 m.

No mortality was observed in control cages.

Eastern oyster mortality, immediately following the blast, was minimal with 1 (5%) dead oyster at 1 and 11 m and two (10%) dead at 23 and 46 m. There was 1 (5%) dead oyster at 1 and 11 m and 3 (15%) dead at 23 and 46 m. There was no control mortality.

Table 4.7.- Percent mortality for white shrimp (Penaeus setiferus), American oysters (=eastern oyster, Crassostrea virginica) and blue crab (Callinectes sapidus) as a function of cage depth (surface and bottom = 24 m), lapsed time, and distance from detonation site. Test organizms were exposed to a 33m strand of 100 g/33 cm Primacord detonation cord laid on the bottom at 24 m depth and perpendicular to the transect of test cages (Modified from Linton et al. 1985a)

				Percent Mortality				
	Number	Cage	Lapsed	Distance (m) from Detonation Site				
Species	Per Cage	Depth	Time(hr)	24	26.4	33.2	51.9	control
White shrimp	20	Surface	0	0	5	0	20	5
			24	5	10	25	20	5
				Distance (m) from Detonation Site				
				1	11	23	46	control
White shrimp	20	Bottom	0	5	30	5	0	0
			24	5	35	10	--	0
Blue crab	20	Bottom	0	40	35	35	10	0
			24	60	50	35	10	0
Eastern oyster	20	Bottom	0	5	5	10	10	0
			24	5	5	15	15	0

Percent mortality at 24 hours is cumulative (e.g., 0 hr + 24 hr) to reflect total mortality at 24 hr. Linton et al. (1985a, Table 1) removed from their cages and counted dead organisms at O hr (instantaneous mortality). Living organisms were returned to the position they occupied at the time of detonation and observed 24 hr later. Their 24 hr values were not cumulative. For surface shots Linton et al. (1985a) gave distances from the explosive to the vertical line maintaining both surface and bottom cages. These values have been modified to provide the actual or slant distances from the explosion to the surfaces cages.

SUMMARY AND DISCUSSION

The results of all the studies reviewed indicate that invertebrates are insensitive to pressure related damage from underwater explosions. This may be due to the fact that all the invertebrate species tested lack gas-containing organs which have been implicated in internal damage and mortality in vertebrates. Underwater explosion produce a pressure waveform with rapid oscillations from positive pressure to negative pressure which results in rapid volume changes in gas-containing organs. In fish, the swimbladder, a gas-containing organ, is the most frequently damaged organ (Christian 1973; Faulk and Lawrence 1973; Kearns and Boyd 1965; Linton et al. 1985a; Yelverton et al. 1975). It is subject to rapid contraction and overextension in response to the explosive shock waveform (Wiley et al. 1981). Species lacking swimbladders or with small swimbladders are highly resistant to explosive pressures (Aplin 1947; Fitch and Young 1948; Goertner 1994). For example, Wiley et al. (1981) and Goertner et al. (1994) noted that hogchokers (Trinectes maculatus), which lack swimbladders, were extremely tolerant of underwater explosions, and greatly exceeded the tolerance of any species with swimbladders that they had tested. Goertner et al. (1994) found that hogchokers were not killed beyond a distance of 1 m from a 4.5 kg charge of pentolite.

Gas-containing organs have also been implicated as a causative factor of internal damage and mortality in other vertebrate species exposed to underwater explosions. Sailors exposed to depth charges and torpedo explosions, while escaping their sinking ships during World War II, suffered damage to gas-containing organs (Cameron et al. 1944; Ecklund 1943; Gage 1945; Palma and Uldall 1943; Yaguda 1945).

The lungs, stomach, and intestines, all gas-containing organs, were ruptured or hemorrhaged, while other organs were relatively unaffected. Similar results have been observed in underwater explosion tests with other mammalian species (Richmond et al. 1973).

Experimental design has progressed little since the early investigative study conducted by Knight (1907). Invertebrate mortality studies have used inadequate sample sizes, lacked adequate controls, and failed to conduct pressure waveform analysis of the explosion (Table 4.8). In addition, investigators have failed to give adequate information concerning testing conditions (e.g., type and weight of explosive, cage type, testing site conditions, post-test invertebrate holding times).

It is essential to not only record invertebrate mortality at given distances from an explosion but to also record the pressure waveform at each test distance. Three parameters of underwater explosive waveforms have been implicated as being responsible for fish mortality: pressure (Teleki and Chamberlain 1978), impulse (Gaspin 1975; Gaspin et al. 1976; Yelverton et al. 1975), and energy flux density (Ogawa et al. 1976, 1977, 1978; Sakaguchi et al. 1976). Peak pressure has been dismissed as a causative mortality factor by Hubbs and Rechnitzer (1952) and Yelverton et al. (1975).

The pressure waveform parameter responsible for invertebrate mortality has not been experimentally determined. The pressure (force per unit area), impulse (strength) and energy flux density (intensity) of the shock-wave are complex physical measures that vary in time. With recent technological advancements in recording equipment and computer programs for waveform analysis, there is no reason why peak pressure, impulse, and energy flux density can not be analyzed and reported. Investigators would make a substantial contribution to the "state of the science" by reporting all aspects of the waveform or by making digital information available to other researchers. This is extremely important, since waveforms change considerably under various test settings (i.e., depth, bottom type, embedment, etc.). In addition, investigators attempting to duplicate study designs to test additional species need precise details of how waveform analysis was conducted.

Pressure waveform-mortality relationships can be used to develop models to predict invertebrate mortality at untested charge sizes and distances from the explosion based on scaling laws of explosives (Cole 1948). It is essential that adequate test distances from the explosion be used and pressure measurements be made at each distance to construct mortality-pressure waveform relationships, or LD50 curves. Without such data collection, little useful information is gained.

Table 4.8.- Summary of study type (experimental or observational), study design, and type of publication for each study reviewed.

Species	Type Study	Adequate Sample Size	Adequate Control	Measured Pressures	Type of Publication	Reference
sea anemone--	Obs.	No	No	No	Refereed	Fry and Cox 1953
corals--	Obs.	No	No	No	Refereed	Fry and Cox 1953
staghorn coral (*Acropora palmata*)--	Obs.	No	No	No	Gray	Brown and Smith 1972
encrusting coral (*Millepora complanta*)--	Obs.	No	No	No	Gray	Brown and Smith 1972
ribbon worms (*Nemertinea sp*).--	Obs.	No	No	No	Gray	Tollefson & Marriage 1949
sand worms (*Nereis sp.*)--	Obs.	No	No	No	Gray	Tollefson & Marriage 1949
tube worms--	Obs.	No	No	No	Refereed	Fry and Cox 1953
Rough abalones (*Haliotis corrugata*)--	Exp.	No	No	No	Refereed	Alpin 1947
Green abalones (*Haliotis fulgens*)--	Exp.	No	No	No	Refereed	Alpin 1947
snail (*Thais sp.*)--	Obs.	No	No	No	Gray	Tollefson & Marriage 1949
snail (conch type)--	Exp.	No	No	No	Gray	Brown and Smith 1972
cockles (*Cardium corbis*)--	Exp.	No	No	No	Gray	Tollefson & Marriage 1949
muc clam (*Macoma sp.*)--	Obs.	No	No	No	Gray	Tollefson & Marriage 1949
commensal clam (*Pseudopythina rugifera*).--	Obs.	No	No	No	Gray	Tollefson & Marriage 1949
oysters (*Ostrea gigas*)--	Exp.	No	No	No	Gray	Tollefson & Marriage 1949
oyster bed (*Ostrea virginica*)--	Exp.	?	?	No	Gray	Gowanloch and McDougal 1946; Gowanloch 1946b, 1948, 1950
oysters (*Ostrea virginica*)--	Exp.	Yes	No	No	Gray	Gowanloch and McDougal 1946; Gowanloch 1946b,

						1948, 1950
oyster (*Ostrea virginica*)--	Exp.	Yes	No	No	Gray	Sieling 1954
oysters (*Ostrea virginica*)--	Exp.	Yes	No	No	Gray	Kemp 1956
oysters (*Ostrea virginica*)--	Exp.	No	No	Yes[1]	Gray	Gaspin 1975
oysters (*Ostrea virginica*)--	Exp.	?[2]	?[2]	No	Gray	Gaspin et al. 1976
American oyster (*Ostrea virginica*)--	Exp.	Yes	Yes	No	Refereed	Linton et al. 1985a
shrimp (*Peneus setiferus*)--	Exp.	Yes	No	No	Gray	Gowanloch and McDougal 1946; Gowanloch 1946a, 1950
white shrimp (*Peneus setiferus*)--	Exp.	Yes	Yes	No	Refereed	Linton et al. 1985a
shrimp (*Peneus sp.*)--	Exp.	Yes	No	No	Gray	Kemp 1956
ghost shrimp (*Upogebia pugettensis*)--	Obs.	No	No	No	Gray	Tollefson & Marriage 1949
blue crab (*Callinectes sapidus*)--	Exp.	Yes	No	Yes[3]	?	Anonymous 1948
blue crab (*Callinectes sapidus*)--	Exp.	Yes	No	No	Gray	Kemp 1956
blue crab (*Callinectes sapidus*)--	Exp.	Yes	No	Yes[1]	Gray	Gaspin 1975
blue crab (*Callinectes sapidus*)--	Exp.	?[2]	?[2]	No	Gray	Gaspin et al. 1976
blue crab (*Callinectes sapidus*)--	Exp.	Yes	Yes	No	Refereed	Linton et al. 1985a
Dungeness crabs (*Cancer magister*)--	Exp.	Small	Yes	No	Gray	Anonymous 1962
crabs (Cancer sp.)--	Exp.	No	No	No	Gray	Tollefson & Marriage 1949
lobster (Homarus americanus)--	Exp.	No	No	No	?	Knight 1907
lobsters (Panulirus interuptus)--	Exp.	No	No	No	Refereed	Aplin 1947
sea urchins--	Obs.	No	No	No	Refereed	Fry and Cox 1953

sea cucumbers--	Obs.	No	No	No	Refereed	Fry and Cox 1953
sea urchin (Lytechinus sp.)--	Exp.	No	No	No	Gray	Brown and Smith 1972

[1]The pressure wave was recorded. However, the gain on some of the recording system channels was set too high and the records were clipped. As such, good pressure measurements were not made.

[2]Mortality is provided as percent mortality. Number of organisms exposed at each distance tested is not provided.

[3]Peak Pressure is provided for the distance nearest and farthest from the explosion.

For example, Aplin (1947) tested only one distance from the explosion and did not record the pressure waveform. It is only possible to conclude that at the distance from the explosion and water depth tested there was no mortality. The data can not be used to extrapolate to other charge sizes or distances from the explosion.

All of the invertebrate studies reviewed were conducted with organisms suspended in the water column or on the substrate and with open-water explosions. Explosives in open water, which are not contained completely by rigid structures, will produce both higher amplitude and higher frequency shock waves than contained detonation. Thus, the use of blasting in structure demolition, when the explosives are enclosed within the structure being razed, should result in lower mortality than when the same explosive detonated in open water. For example, "burning" a steel beam underwater with perimeter charges to sever it would cause higher mortality than the severance of a concrete pier using an explosive of the same weight placed within the pier by drilling and covering. The more work accomplished by a detonation in cracking and moving a rigid volume, and the greater the energy dissipated into solid media, the lower the capacity of the water-borne shock wave will have to cause mortality. Explosives buried in the substrate or placed in bore holes and adequately stemmed (Keevin, In press) produce less impact than open-water explosions. For example, Traxler et al. (1992) found no mortality or internal injuries in largemouth bass (Micropterus salmoides), bluegill (Lepomis macrochirus) or channel catfish (Ictaluris punctatus) in a cage 7.6 m from each of two shot holes drilled 27.4 and 33.5 m into the sediment and charged with 4.5 and 9.1 kg of dynamite.

Natural resource managers making impact assessments based on the existing literature should consider that explosive demolition and seismic testing using explosives buried in the sediment will produce effects less than open-water shots.

CHAPTER 5

THE ENVIRONMENTAL EFFECTS OF UNDERWATER EXPLOSIONS: AMPHIBIANS AND REPTILES

INTRODUCTION

To date, there has not been a single comprehensive study to determine the effects of underwater explosions on either amphibians or reptiles that defines the relationship between distance/pressure and mortality or damage.

INJURY AND MORTALITY OF REPTILES EXPOSED TO UNDERWATER EXPLOSIONS

There have been a number of studies which demonstrate that sea turtles are killed and injured by underwater explosions (Duronslet et al 1986; Gitschlag 1990; Gitschlag and Herozeg 1994 ; Gitschlag and Renaud 1989 ; Klima et al. 1988; O'Keeffe and Young 1984) . Currently, there is no information available for amphibians (i.e., frogs, salamanders, etc.). There are few reports of turtle mortality because turtles can be difficult to observe, and turtles killed by explosions may not float to the surface until sufficient bacterial activity has occurred, which takes several days (NRC 1990). The NRC has concluded that data on the effects of underwater explosions, in relation to oil and gas platform explosive removal, are inadequate and that further research is needed.

In March and April of 1986, 51 dead sea turtles, primarily Kemp's ridleys, washed ashore on Texas beaches after the removal of platforms that involved 22 underwater explosions. Because shrimp fishing (another cause of sea turtle mortality) was at a very low level in the area, the explosions were identified as the probable cause (Klima et al. 1988).

To document the effects of underwater explosions on sea turtles, the National Marine Fisheries Service undertook an experiment to determine the extent of injuries to sea turtles placed at 700 ft. 1,200 ft. 1,800 ft. and 3,000 ft (213.4, 365.8, 548.6, and 914.4 m) from an explosive removal of an oil platform (Klima et al. 1988). On June 21, 1986, a platform in 30 ft (9.1 m) of water was removed by detonating 50 lb (22.7 kg) of nito-methane inside each of four jacket legs 15 ft (4.6 m) below mudline. One Kemp's ridley and one loggerhead were placed in a cage at each of the four distance. Just before detonation, the cages were lowered to a mid-water depth of 15 ft (4.6 m). The cages were retrieved shortly after detonation. The four turtles within 1,200 ft (365.8 m) of the explosion were unconscious, as was the loggerhead in the cage at 3,000 ft (914.4 m). If they had been left in the water these turtles may have drowned. Turtles in all of the cages were affected. Some suffered averted cloaca and vasodilation, which lasted for two to three weeks.

Two observations of sea turtles severely wounded by explosive removals of platforms have been made. A dead or injured turtle drifting about 10 ft below the surface was sighted 1.5 hr after the explosive removal of a structure in 1986 (Gitschlag and Renaud 1989). At a removal site of a caisson in 1991, a loggerhead with a fracture down the length of its carapace surfaced within one minute of detonation (Gitschlag, personal communication in NRC 1996).

Two immature green turtles (100 to 150 ft) (30.5 to 45.7 m) were killed when 20 lb (9.1 kg) of plastic explosives (C-4) were detonated in open water by a U.S. Navy Ordnance Disposal Team. Necropsies revealed extensive internal damage, particularly to the lungs (Schroeder, personal communication in NRC 1996).

Three sea turtles were unintentionally exposed to underwater shock tests by the Naval Coastal Systems Center in 1981 off the coast of Panama City, Florida. Three detonations of 1,200 lb (544.3 kg) of TNT at mid-depth (in approximately 120 ft (36.6 m) of water) injured one turtle at a distance of 500 to 700 ft (152.4 to 213.4 m) and another at 1,200 ft (365.8 m). A third turtle at 2,000 ft (609.6 m) was apparently uninjured (O'Keeffe and Young 1984; Klima et al. 1988).

Young (1991) developed the following equation to estimate sea turtle safe ranges.

$$R_t = 560\ W_E^{1/3}$$

R_t = Range in feet
W= Weight of explosive in pounds

The metric form of this equation for the safe sea turtle range is

$$R_t\ (m) = 222\ W(\text{in kg})^{1/3}$$

The estimated sea turtle safe range equation was based on Gulf of Mexico oil platform criteria established by the National Marine Fisheries Service (NMPS). As the sea turtle literature review indicated, there has not been a single study establishing the relationship between underwater explosive pressures and mortality. Young (1991) suggested that the calculated sea turtle safe ranges should only be used for preliminary planning purposes.

There are no data on nonlethal damage from underwater explosions or delayed mortality, both of which may have a greater impact on sea turtle populations than immediate death from explosions.

INJURY AND MORTALITY OF AMPHIBIANS EXPOSED TO UNDERWATER EXPLOSIONS

There currently is no data available on the effects of underwater explosions on amphibians (i.e., frogs, salamanders, etc.). Although untested, amphibians with air-containing organs, such as lungs, probably have mortality comparable to fish with swimbladders. For impact assessment purposes, the relationship between distance/pressure and fish mortality/injury are probably fairly close (See Chapter 6 for details). Although untested, amphibians without air-containing organs, are probably immune to underwater explosives as are benthic fish species without swimbladders (Goertner et al. 1994).

MITIGATION TECHNIQUES TO PROTECT REPTILES AND AMPHIBIANS FROM UNDERWATER EXPLOSIONS

Reptiles

The simplest method to protect sea turtles from underwater explosions is to either avoid periods when they are in the blasting zone or to remove the sea turtles. Avoidance of sea turtles can be achieved in two manners. Depending on location, there may be time periods when sea turtles are not in the project area due to their life history characteristics (e.g. migration patterns). This can be determined by coordination with the state natural resource agency or NMFS. Blasting can be planned during time periods of low sea turtle abundance. If sea turtles are potentially in the area during blasting, an aerial survey using a light plane or helicopter can be conducted prior to detonation. If sea turtles are observed in the project area, blasting can be halted until they move out of a pre-determined blast zone. As a last resort, turtles can be physically captured and removed from the

blast zone prior to detonation.

The NMFS developed a series of mitigation features for a Incidental Take Statement under the auspices of the Endangered Species Act to protect sea turtles from the use of underwater explosives during salvage of offshore oil and gas structures (Table 5.1).

An example of the above strategy is in place for explosive removal of oil and gas structures in state and federal waters of the Gulf of Mexico (Gitschlag 1990). For at least 48 hr prior to detonation, NMFS observers watch for sea turtles from the surface. Helicopter aerial surveys within a mile radius of the removal site are conducted 30 min prior to and after detonation (Gitschlag and Herczeg 1994). If sea turtles are observed, detonations are delayed until the sea turtles have been safely removed or have left the area.

Amphibians

Mitigation techniques described for fish in Chapter 8 are applicable to amphibians with air-containing organs.

Table 5.1.- Summary of "generic" incidental take statement. From Gitschlag and Herczeg (1994)

1. Qualified observers monitor for sea turtles beginning 48 hours prior to detonations.
2. Thirty minute aerial surveys within one hour prior to and after detonation.
3. If sea turtles are observed within 914 meters of the structure, detonations will be delayed and the aerial survey repeated.
4. No detonations will occur at night.
5. During salvage-related diving, divers must report sea turtle and dolphin sightings. If sea turtles are thought to be resident, pre- and post-detonation diver surveys must be conducted.
6. Detonation of sequential explosive charges must be staggered by at least 0.9 seconds to minimize cumulative effects of the explosions.
7. Avoid use of "scare" charges to frighten away sea turtles which may actually be attracted to feed on dead marine life.
8. Removal company must file a report summarizing the results.

CHAPTER 6

THE ENVIRONMENTAL EFFECTS OF UNDERWATER EXPLOSIONS: FISH

INTRODUCTION

The potential for injury and mortality to both marine and freshwater fishes, resulting from underwater blasts, has been well documented (Hubbs and Rechnitzer 1952; Ferguson 1962; Teleki and Chamberlain 1978).

PRESSURE RELATED MORTALITY OF FISH

Three parameters of underwater explosive waveforms have been implicated as being responsible for fish mortality: pressure (Teleki and Chamberlain 1978), impulse (Gaspin 1975; Gaspin et al. 1976; Yelverton et al. 1975), and energy flux density (Ogawa et al. 1976, 1977, 1978; Sakaguchi et al. 1976). Peak pressure has been dismissed as a causative mortality factor by Hubbs and Rechnitzer (1952) and Yelverton et al. (1975). Hubbs and Rechnitzer (1952) found that in marine fish species tested, the lethal threshold peak pressure from dynamite (DV = approximately 17,000 m/s) explosions varied from 276 to 483 kPa. Peak pressures from slowly detonating black powder (DV = 1,709 m/s), producing pressures as high as 855 to 1,103 kPa, did not kill caged fishes.

Based on the findings of Hubbs and Rechnitzer (1952), Teleki and Chamberlain (1978) concluded that the lethality of an explosive is directly related to its detonation velocity. Detonation velocity (DV) is the rate at which a blasting agent ignites. It ranges from about 1,650 to 7,650 m/s for products used commercially today (Dick et al. 1993a). Teleki and Chamberlain (1978) suggested that the more rapid the detonation velocity the more abrupt was the resultant hydraulic pressure gradient and the more difficulty fish had adjusting to the pressure changes. They felt that a knowledge of the detonation velocity is critical to a true understanding of the impact of blasting on fish.

Keevin (1995) tested Teleki and Chamberlain's (1978) suggestion by comparing the mortality of bluegill (Lepomis macrochirus) exposed to three high-explosive types (T-100 Two Component, Pellite, and Apex 260) spanning the range of detonation velocities within commercially available explosives (Table 6.1).

Table 6.1.- Characteristics of explosives used during testing. (Atlas Powder Company 1990a,b; Slurry Explosive Corporation 1991)

	Pellite	APEX 260	T-100
Detonation Velocity (m/s)	3,6	5,033	6,314
Density (gm/cm^3)	0.81-0.85 1.25		1.22
Relative Bulk Strength 1.00 (ANFO=1)	1.00	1.45	1.60

Using equivalent weights of explosives, there was no significant difference in mortality curves based on distance from the explosive charge. The results suggest that detonation velocity of commercially available explosives, with the exception of black powder, is not an important factor in fish mortality. The misconception concerning the relationship between lethality and detonation velocity is "probably" based on field observations and research (Baldwin 1954; Fry and Cox 1953; Ferguson 1962; Hubbs and Rechnitzer 1952) which indicated that black powder, a low

detonation velocity explosive, had little effect on fish. Ferguson (1962) found that caged yellow perch (Perca flavescens) were unaffected by 45 kg charges of black powder, fired with an electric squib (detonator). Black powder charges detonated with a nitrone detonator, itself a high explosive, were damaging to fish. Even a 0.45 kg nitrone charge killed caged perch up to 60.7 m away. Fry and Cox (1953) reported that fish and game observers, attached to seismic operations which normally used 40 to 50 shots of 20.3 or 40.5 kg charges of black powder per day, reported almost no damage to fish. On one occasion, three divers located a school of rockfish (Sebastodes sd.) in approximately 16.7 m of water. A 20.3 kg charge was detonated above the school at a depth of 1.8 m. The divers descended and found no mortality in the school. Baldwin (1954) observed "many salmon (Oncorhynchus) swimming about in the blasting area prior to detonation" of either a 20.3 or 40.5 kg charge of black powder at a depth of 1.8 m. None were harmed by the explosion.

The difference in fish mortality between black powder, a low explosive, and high explosives appears to be related to the waveform produced by each explosive type. Black powder produces a pressure waveform with a slow rise time and low amplitude whereas high explosives have an abrupt rise time, high amplitude, and short frequency. In addition, high explosives have a much higher negative pressure than black powder, as shown in Figures 8 and 9 in Hubbs and Rechnitzer (1952). The amplitude and short frequency of the negative pressure wave and resulting damage to the swim bladder may be the causative factor of mortality in fish exposed to high-explosive pressure waveforms.

The exact pressure waveform measurement responsible for fish mortality is unknown. As previously noted, peak pressure is not a good predictor of mortality when comparing very different types of explosives (Hubbs and Rechnitzer 1952). Baxter et al. (1982) reviewed overpressure waves versus damage effects data and concluded that impulse strength was the most predictive damage parameter for water depths of less than 3 m. Energy flux density was found to be more accurate in predicting effects on fish in water depths greater than 3 m. Yelverton et al. (1975) compared peak pressure and impulse as mortality predictors by keeping the depth of charge and slant range constant and by varying the depth of the fish, thus varying the impulse levels and keeping the peak pressure constant. The impulse for 50-percent lethality in carp (Cyprinus carpio) was 189 Pa-s (at 52. m), 162 Pa-s (at 305. m) and 181 Pa-s (at 3.05 m). In contrast, the corresponding peak pressures associated with these LD50 impulses varied markedly, 5.58 Mpa (at 52 m), 2.31 Mpa (at 305. m) and 1.21 Mpa (at 3.05 m) for carp tested at 3.05 m depths.

Keevin (1995) compared mortality of bluegill (Lepomis macrochirus) exposed to a 2 kg charge of T-100 detonated at 2 m depth with various measurements of the pressure waveform. He demonstrated that there was a significant correlation ($P > 0.05$) between all values of impulse and energy flux density and mortality, with the exception of impulse calculated as 50 (Table 6.2). However, Keevin exposed the bluegill to explosive pressures at only one depth.

Table 6.2.- Spearman correlation matrix of number of dead (n=25) versus waveforms. Spearman correlations larger than 0.619 are significant at $p < 0.05$. (Modified from Keevin (1995))

Waveform	**Shot 1**	**Shot 2**
Peak pressure	0.903	0.651
Impulse (first positive wave)	0.9	0.806
Impulse (calculated by the greatest difference of peak pressure to pressure low)	0.878	0.892
Impulse (5e)	-0.195	-0.554
Impulse 6.7e	-0.805	-0.843
Energy Flux Density	0.878	0.892

The rapid oscillation in the pressure waveform between a high overpressure and underpressure associated with detonation of high explosives is most probably responsible for fish mortality. This oscillation in waveform is responsible for the rapid contraction and overextension of the swimbladder resulting in internal damage and mortality. Any waveform value that provides a good predictor of mortality over a wide range of conditions (i.e., organism depth, explosive size, explosion depth) would be a suitable measure. Currently, it appears that impulse provides the best measurement for shallow shots and energy flux density provides the best measurement for deep water shots. However, this is an area that needs further evaluation.

EXPLOSIVE PRESSURE RELATED ORGAN DAMAGE

Investigators have found the swimbladder to be the most frequently damaged organ (Christian 1973; Faulk and Lawrence 1973; Kearns and Boyd 1965; Linton et al. 1985a; Yelverton et al. 1975). The swimbladder, a gas-containing organ is subject to rapid contraction and overextension in response to the explosive shock waveform (Wiley et al. 1981). Gas-containing organs have also been implicated as a causative factor of internal damage and mortality in other vertebrate species exposed to underwater explosions. Sailors exposed to depth charges and torpedo explosions, while escaping their sinking ships during World War II, suffered damage to gas-containing organs (Cameron et al. 1944; Ecklund 1943; Gage 1945; Palma and Uldall 1943; Yaguda 1945). The lungs, stomach, and intestines were ruptured or hemorrhaged, while other organs were relatively unaffected. Similar results have been observed in underwater explosions tests with other mammalian species (Richmond et al. 1973).

Because the swimbladder was burst outward, some investigators have suggested that negative phase (relative to ambient) of the pressure wave is responsible for damage to the swimbladder (Anonymous 1948; Hubbs and Rechnitzer 1952; Wiley et al. 1981). For example, postmortem observation of striped bass (Roccus saxatilis) and trout (Cynoscion regalis) found "the edges of holes in the swim bladder were turned outward and that blood from broken vessels in the wall of the bladder had been blown into the abdominal cavity" (Anonymous 1948).

Laboratory tests have demonstrated that small negative pressures can injure swimbladders. Tsvetkov et al. (1972) applied pressure of 1-6 atmospheres (101.4-608.4 kPa) above the surface of water containing fish in a closed container over a period of 2-5 min. After the pressure was applied, fish were allowed to adapt until they reached neutral buoyancy. Pressure was then released at rates of 0.1-6.0 atm/s (10.1-608.4 kPa/s). One hundred percent mortality of roach (Rutilus rutilus) was observed when the rate of discharge was 3 atm/s (304.1 kPa/s), 40-72% at a rate of 0.1-0.5 atm/s (10.1-50.7 kPa/s), and 10% at a rate of less than 0.1 atm/s (10.1 kPa/s). Rupture to the swimbladder walls was observed at their weakest point in

response to the large increase in volume. Hubbs and Rechnitzer (1952) found that negative pressures of only one atmosphere (101.4 kPa) killed marine fish. Brown (1939) showed that the guppy could not successfully adapt to decompressions of more than about one-half atmosphere (50.7 kPa). Hogan (1941) applied negative pressures of up to one atmosphere (101.4 kPa) to a variety of fish species, for periods of 10 to 30 seconds and found that physoclistous fish suffered hemorrhage in the circulatory system and often died. Muir (19S9) found that young salmon could usually survive decompressions of about one atmosphere (101.4 kPa); but when the pressure was lowered to the vapor pressure so that the water cavitated, mortality was high.

The rate and magnitude of pressure change in laboratory studies, both positive and negative, does not approach those observed in underwater explosions. In addition, laboratory studies do not duplicate the rapid oscillation from positive pressure to negative pressure which result in rapid volume changes in the swim bladder. Underwater explosions should be far more damaging.

Species lacking swimbladders or with small swimbladders are highly resistent to explosive pressures (Aplin 1947; Fitch and Young 1948; Goertner et al. 1994). For example, Aplin (1947) noted that two opal-eye perch (<u>Girella nigricans</u>), 15.24 m from a 9 kg charge of 60% petrogel, were killed and their viscera reduced to a "pulp". However, 4 sculpin (<u>Scorpaena guttata</u>) and a cabezone (<u>Scorpoenicthys marmoratus</u>), which both lack swimbladders, in the same cage were not injured nor was there any damage to their internal organs. Wiley et al. (1981) and Goertner et al. (1994) noted that hogchokers (<u>Trinectes maculatus</u>), which lack swimbladders, were extremely tolerant of underwater explosions, and greatly exceeded the tolerance of any species with swimbladders that they had tested. Goertner et al. (1994) found that hogchokers were not killed beyond a distance of 1 m from a 4.5 kg charge of pentolite. Immediate death appeared to be caused by loss of blood resulting from hemorrhaging in the gills. Goertner et al. (1994) suggest that the lack of hogchoker injuries, except when close to an explosive charge, is probably due to the absence of obvious air cavities. They imply that the observed damage may be caused by the presence of microbubbles. Microbubbles have not been confirmed for fish but are known to occur in humans, where they have a radii of a few micrometers (Lewin and Bjorno 1981). Microbubble response to microsecond pulses of ultrasound has become a concern in the field of diagnostic medicine using ultrasound (Flynn and Church 1988). Investigators have defined a "transient cavity" as one that expands to a critical maximum radius and then collapses violently. The gas temperature and pressure reach extremely high values and a shock wave is generated in the surrounding medium during collapse and rebound. Ayme-Bellegarda (1990) and Holland and Apfel (1990) suggest that a bubble in the presence of a boundary can be more damaging because of the formation of a jet in the collapsing bubble which is directed toward the boundary.

Keevin et al. (In preparation) exposed 25 caged bluegill placed 2 m below the water surface to a 2 kg charge of T-100 explosive detonated at 2 m depth. Pressure waveform values (Table 6.3) can be compared with internal damages (Table 6.4) or mortality (Table 6.5) to determine damaging pressure levels. An abrupt increase in internal damage (ruptured swimbladder, kidney, liver, and spleen damage) occurred at values above approximately 700 kPa peak pressure, 50 Pa-s impulse (first positive wave), and 40 J/m^2 energy flux density. Mortality abruptly increased at approximate values above 500 kPa peak pressure, 40 Pa-s impulse (first positive wave), and 20 J/m^2 energy flux density. The lower threshold values for mortality reflect the mortality scoring system which scores minor injuries as "dead". LD50 values are presented for each pressure waveform measurement are given in Table 6.6.

Table 6.3.-Pressure waveform values resulting from the underwater detonation of a 2kg charge of T-100 at a depth of 2m. Independent duplicate trials are reported. (Keeven et al. (In preparation))

	DISTANCE (Meters) FROM EXPLOSION								
	30.0	32.5	35.0	37.5	40.0	42.5	45.0	47.5	Control
SHOT 1									
Peak Pressure (kPa)[1]	1300.0	860.0	900.0	693.0	572.0	518.0	340.0	368.0	0
Impulse (Pa-s)[2]	98.6	59.1	49.7	56.1	39.2	38.1	23.6	23.1	0
Energy Flux Density (J/m^2)	134.0	63.9	62.8	45.5	28.1	17.7	9.1	8.1	0
SHOT 2									
Peak Pressure (kPa)1	1130.0	861.0	869.0	899.0	383.0	577.0	398.0	410.0	0
Impulse (Pa-s)[2]	113.0	60.6	67.9	55.4	23.8	45.7	28.3	25.8	0
Energy Flux Density (J/m^2)	128.0	69.4	65.0	42.2	19.0	24.6	10.6	10.0	0

[1] Peak pressure for the first positive waveform
[2] Impulse was calculated by integrating the pressure-time curve for the first positive wave.

Table 6.4.- Bluegill damage counts for each distance tested and controls (n=25 at each distance) based on necropsies of fish preserved 1 hr post blast. Bluegill were exposed to a 2 kg charge of T-100 at 2 m. Independent duplicate trials are reported. (Keevin et al. (In preparation))

	DISTANCE (Meters) FROM EXPLOSION								
	30.0	32.5	35.0	37.5	40.0	42.5	45.0	47.5	Control
SHOT 1									
External Damage	9	3	1	0	0	0	0	0	0
Ruptured Swimbladder	22	14	13	9	1	0	0	0	0
Free Blood In Swimbladder	21	24	23	17	2	0	0	0	0
Free Blood In Coelom	12	4	12	6	6	0	0	0	0
Kidney Damage	16	8	8	0	0	0	0	0	0
Liver Damage	13	14	14	0	0	0	0	0	0
Spleen Damage	13	17	19	0	0	0	0	0	0
Heart Damage	1	0	0	0	0	0	0	0	0
Free Blood in Pericardium	2	0	0	0	0	0	0	0	0
Brain Damage	0	0	0	0	0	0	0	0	0
SHOT 2									
External Damage	12	4	5	0	0	0	0	0	0
Ruptured Swimbladder	23	21	19	4	0	0	0	0	0
Free Blood In Swimbladder	21	25	25	16	6	0	0	0	0
Free Blood In Coelom	13	5	7	8	8	3	0	0	0
Kidney Damage	21	12	10	0	0	0	0	0	0
Liver Damage	14	15	17	0	0	0	0	0	0
Spleen Damage	9	11	17	1	0	0	0	0	0
Heart Damage	0	0	0	0	0	0	0	0	0
Free Blood in Pericardium	5	0	0	0	0	0	0	0	0
Brain Damage	0	0	0	0	0	0	0	0	0

Table 6.5.- Percent mortality of bluegill (n=25 at each distance) exposed to a 2 kg charge of T-100 detonated underwater at 2 m depth. Independent duplicate trials are reported. (Keevin et al. (In preparation))

	DISTANCE (Meters) FROM EXPLOSION								
	30.0	32.5	35.0	37.5	40.0	42.5	45.0	47.5	Control
SHOT 1									
Percent Mortality	100.0	88.0	92.0	96.0	36.0	0.0	0.0	0.0	0.0
SHOT 2									
Percent Mortality	96.0	100.0	100.0	80.0	40.0	12.0	0.0	0.0	0.0

Table 6.6.- Bluegill LD50 values resulting from detonation of a 2 kg charge of T-100 at 2 m depth. Independent duplicate trials are reported. Keevin et al. (In preparation)

	LD50	Lower Limit	Upper Limit
SHOT 1			
Distance(m)	38.96	37.95	40.00
Peak Pressure(KPa)	625.80	591.60	661.90
Impulse(Pa-s)[1]	44.09	39.00	49.00
Energy Flux Density(J/m^2)	33.30	29.40	37.60
SHOT 2			
Distance(m)	39.23	38.21	40.28
Peak Pressure(KPa)	583.23	131.00	957.94
Impulse(Pa-s)[1]	49.00	46.30	51.80
Energy Flux Density(J/m^2)	28.00	10.42	56.06

[1]Impulse was calculated by integrating the pressure-time curve for first positive wave.

Necropsy results for bluegill in this study agree with those of other investigators who found the swimbladder to be the most frequently damaged organ (Christian 1973; Faulk and Lawrence 1973; Kearns and Boyd 1965; Linton et al. 1985a; Yelverton et al. 1975). The direction of rupture of bluegill swimbladders could not be determined; probably due to the thin and delicate nature of the swimbladder wall and fixation. Damage to the kidney, liver and spleen was extensive and possibly related to the rapid contraction and expansion of the swim bladder. In bluegill, the swimbladder is in close contact with the kidney located dorsally and the alimentary system ventrally. Table 6.4 shows that at distances where swimbladder ruptures occur, other internal damages also occur (i.e., liver kidney and spleen), and as the rate of swimbladder damage falls so do other injuries.

Ogawa et al.(1978) found that in fish with less well-developed swimbladders, neither the kidneys nor air bladder are injured, indicating that the presence of a swimbladder plays an important role with reference to injuries to other organ systems. Wiley et al. (1981) suggested that susceptibility to injury was related to body rigidity and swimbladder position relative to other organs. For example, oyster toadfish (Opsanus tau), a species which is extremely resistant to damage, have swimbladders that are less adherent to the dorsal body wall and therefore were

less in direct contact with the kidney. Wiley et al. (1981) suggested that the thick walls of their swimbladders reduced the incidence of rupture and the inherent flexibility of their bodies cushioned the internal organs from damage caused by rapid fluctuations in the size of the swimbladders. Incidence of internal hemorrhaging and bruising of the kidneys was much greater in the more rigidly built fish in which the swimbladder was closely adherent to the kidney. Apparently, the rapid expansion and contraction of the swimbladder is also responsible for damage to other organs. Knight (1907) and Fitch and Young (1948) have also suggested that the thickness of the swimbladder may also be an important factor in determining mortality levels, with species having thin swimbladders being most susceptible to blasts.

Teleki and Chamberlain (1978) suggested that physoclistous fish species (swim bladder attached to the circulatory system allowing slow change in bladder pressure) are more sensitive to blast pressures than either physostomus species (swim bladder attached to the esophagus allowing quick release of air) or species with no swimbladder. In their testing program, pumpkinseed (Lepomis gibbosus), white bass (Morone chrysops), and crappie (Pomoxis annularis), all physoclistic, were the most sensitive to blasting than physostomus species i.e., rainbow trout (Salmo gairdneri), white suckers (Catostomus commersoni), and yellow bullheads (Ictalurus natalis). In tests with a number of species, Yelverton et al. (1975) concluded there was little or no difference between the impulse required for 50% mortality for fish having dusted swimbladders and fish having non-ducted swimbladders. Christian (1973) suggested that intuitively he would expect that at the outer limits of the lethal zone a physostomous species might be more capable of adapting to the pressure changes than would a physoclistous species, but that under more severe shock conditions the two types might suffer about equal damage. He also stated that it may not matter in the explosion damage process, since pressure changes occur within microseconds, too rapidly for the normal gas-exchange mechanisms to operate. Baxter et al. (1982) suggested that the small duct of a physostomous species would not pass a significant amount of gas during the transit of shock waves.

External damage appears to be species specific and related to the magnitude of the pressure wave (e.g., charge size and distance from explosion). Linton et al. (1985a) noted that external injury to black drum (Pogonias cromis) exposed to primacord detonations was minor, whereas internal injury was substantial. The only visible external damage was loss of opercular scales. Red drum (Sciaenops ocellatus) exhibited no visible external injuries. The presence of a swimbladder may be a causative factor of some types of external damage. A bright red circle was observed on both sides of bluegill, presumably dermal capillary rupture caused by the rapid expansion and contraction of the swim bladder (Keevin et al. In preparation). After preservation, the circle appeared as an area of pallor or discoloration. Tyler (1960) observed a loss of small patches of scales in the vicinity of the swimbladder from each side of red salmon (Oncorhynchus nerka) exposed to 40-percent gelatin dynamite charges.

EFFECT OF FISH SIZE

There is limited information that fish weight may also influence vulnerability. Yelverton et al. (1975) tested a number of different fish species and found that a higher impulse was required to kill larger fish (body weight) than small fish. This was true both within a species and between species tested. Other factors such as age, general health, water temperature, and reproductive condition may influence mortality.

EFFECTS OF UNDERWATER EXPLOSIONS ON LARVAL FISH AND EGGS

Kostyuchenko (1973) exposed anchovy, blue runner and carucian carp eggs to a 50 g charge of TNT. The TNT charge produced structural abnormalities in the anchovy eggs at a distance of 2 to 20 m from the source, in the blue runner eggs up to 10 m away, and in the crucian carp eggs up to 5 m away. Only 20% of the eggs used in the experiment survived at a distance of 2 m, 58.2% at a distance of 10 m; only at a distance of 20 m were there no sharp differences from the control.

The "Guidelines for the Use of Explosives in Canadian Fisheries Waters" (Wright In press) have a guideline for protecting eggs on spawning beds. "No explosive may be use that produces, or is likely to produce, a peak particle velocity greater than 13 mm-sec^{-1} in a spawning bed during egg incubation." The guidelines provide the following table of set-back distances to achieve the standard (Table 6.7).

There have been no comprehensive studies determining the relationship between underwater pressures and larval fish mortality.

Table 6.7.- Set-back distance (meters) from center of detonation to spawning habitat to achieve 13mm-sec^{-1} standard for all types of substrate. (From Wright (In press))

Explosive Charge Weight (kg)	0.5	1	5	10	25	50	100
Set-back Distance (m)	15	20	45	65	100	143	200

SUBLETHAL INTERNAL DAMAGE TO FISH FROM UNDERWATER EXPLOSIONS

Sverdrup et al. (1994) conducted laboratory studies to determine the effects of underwater explosions on the vascular endothelium and on primary stress hormones of farmed Atlantic salmon (*Salmo salar*). Acclimated salmon were exposed to a series of 10 underwater explosions over 70 min. each of 2 MPa in pressure amplitude, in a laboratory tank. No mortality occurred immediately or during the subsequent 7 days of observation.

Structurally, the vascular endothelium of the ventral aorta and the coeliaco mesenteric artery revealed signs of injury within the first 30 min after the experimental shock. The endothelial impairment was temporary, persisting throughout the first days while being restored after 1 week.

Functionally, the cholinergic and adrenergic vasoconstrictor responses in the coeliaco mesenteric artery were markedly reduced during the first day after the shock. The loss of structural integrity and the reduced functional response indicated a temporary impairment of the vascular endothelium in response to the underwater explosion.

The primary stress hormones, adrenaline and cortical, were not immediately elevated in plasma, but revealed different patterns of delayed increases. The head kidney content of catecholamines was not altered by the acoustic shock, while the atrial uptake of both catecholamines declined progressively during the 48 h of observation. Plasma chloride was not affected.

UNDERWATER EXPLOSIVE FISH MORTALITY MODELS

Based on predictive equations, the kill radius for an underwater explosion can be calculated prior to commencement of the project. Three such predictive models are available: the energy flux density model (Sakaguchi et al. 1976), the impulse strength model (Baxter et al. 1982; Hill 1978; Munday et al. 1986; Wright 1982; Yelverton et al. 1975), and the dynamical model (Wiley et al. 1981). A user-friendly computer program was developed by COASTLINE Environmental Services Ltd. (1986) that uses the impulse strength model (IBlast) and the energy flux energy flux density model (EBlast) to predict effects for both midwater charges and charges that are drilled and buried in rock substrate. Although there are problems associated with these models (Hempen and Keevin 1995; Keevin 1995), they do give an approximation of the potential fish kill radius of a given explosive charge. O'Keeffe (1984) and Young (1991) provide kill probability contours for various fish sizes and charge weights based on the predicted results obtained by the dynamical model.

Young (1991) developed an equation to estimate safe ranges for fish with swimbladders. He noted that the prediction model was based on experimental data and an injury mechanism related to the response of swimbladder gas to the direct and reflected shock waves. Estimated range of vulnerability based on 90 percent probability of survival at a relatively shallow depth. He indicated that small fish are more vulnerable than large fish and fish near the surface are more vulnerable than deep fish.

Young (1991) suggested that the following fish (with swimbladder) safe range (Table 6.8) be used for preliminary planning purposes. He suggestedthat the equations are technically correct but they do not cover all possible conditions or marine environments.

Table 6.8.- Safety zone range calculations for fish with swimbladders. (From Young 1991)

ENGLISH MEASUREMENTS

$$R_{safe} = 95\ W_f^{-0.13} W^{0.28} d_w^{0.22}$$

R_{safe} = Safe range in feet
W = Weight of explosive in pounds
W_f = Weight of fish in pounds
d_w = Depth of burst in feet

METRIC MEASUREMENTS (Conversions)

$$R_{safe} = 43\ W_f^{-0.13} W^{0.28} d_w^{0.22}$$

R_{safe} = Safe range in feet
W = Weight of explosive in pounds
W_f = Weight of fish in pounds
d_w = Depth of burst in feet

Hill (1978) developed a model to predict lethal ranges for fish based on data in Yelverton et al. (1973). The model has been reproduced in Wright (1982) and has been reproduced here. Hill (1978) indicated that the model will "underestimate lethal ranges if the water depth is shallow (less than five times either the detonation depth or target depth, whichever is greater), and the bottom is rocky. In cases like this, there may be a considerable bottom-reflected shock wave which will increase the impulse at any point. If the charge is to be detonated under thick ice, a positive rather than negative surface-reflected wave may result. Once again, this increases the impulse and, in turn, the lethal range. Under these conditions, the calculated lethal ranges or safe distance should be doubled to ensure a conservative safety margin."

To use Hill's model to calculate lethal ranges or safe distance, the following information is required:

1. typical size (weight) of the fish species likely to be in the area,
2. depth of the target fish,
3. depth of detonation of the charge, and
4. weight of the charge.

To determine the slant range, the following steps are required:

1. From Figure 6.1, determine the impulse (I) corresponding to the assumed damage level.
2. Calculate the scaled impulse by dividing the impulse found in Step 1 by the cube root of the charge weight.

   $(I_{sc} = I/wt^{1/3})$

3. Calculate <u>parameter 'A'</u>, which is derived from the depth of the target fish, the depth of the detonation and the charge weight such that:

   $$A = \frac{\text{target depth (m) x detonation depth (m)}}{\text{charge weight (kg)}^{2/3}}$$

4. From Figure 6.2 find the best-fit curve to the calculated value of 'A' and using this curve, determine the value of the Scaled Range (R_{sc}) corresponding to the <u>Scaled Impulse</u> (I_{SE}) determined in Step 2.
5. Calculate the range (R) in meters by multiplying the Scaled Range by cube root of the charge weight.

   $R(m) = R_{sc} \text{ x charge wt}^{1/3}$

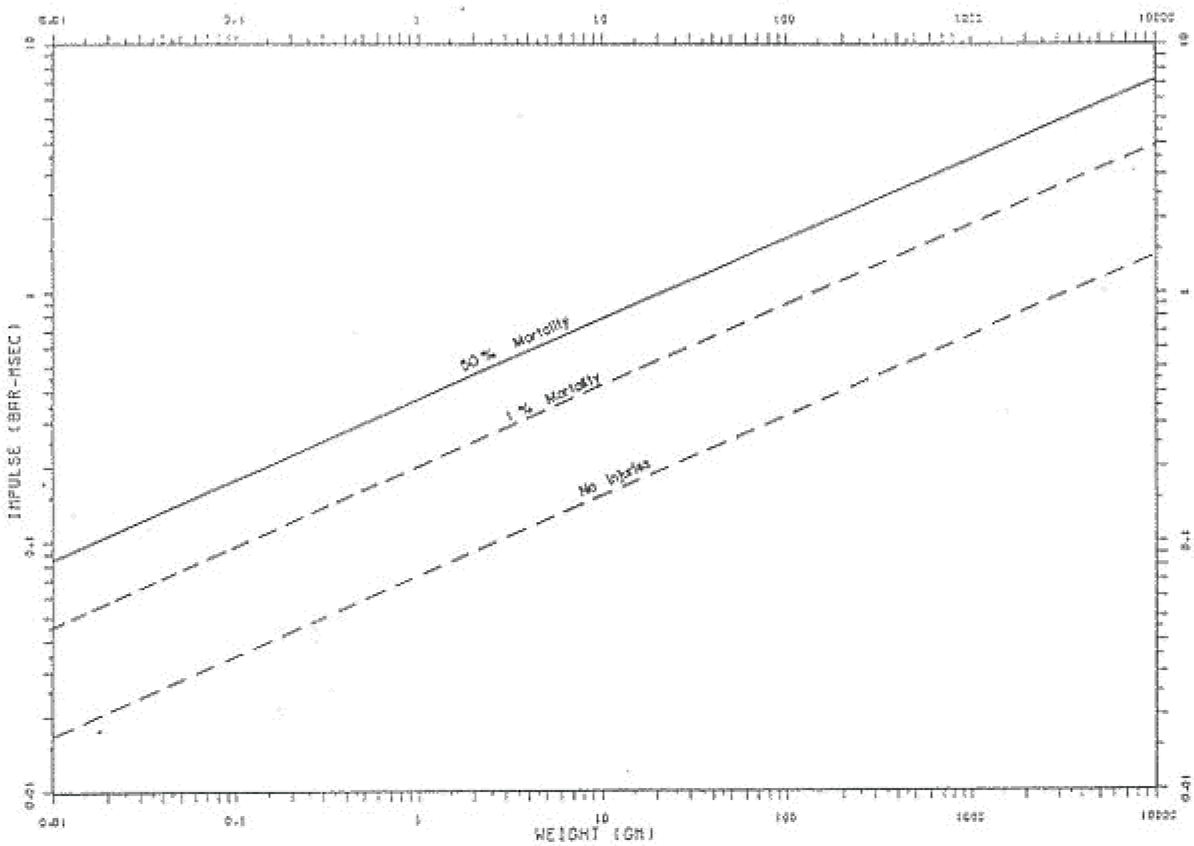

Figure 6.1.-Lethal impulse versus weight for fish (from Hill ; after Yelverton et al. 1975).

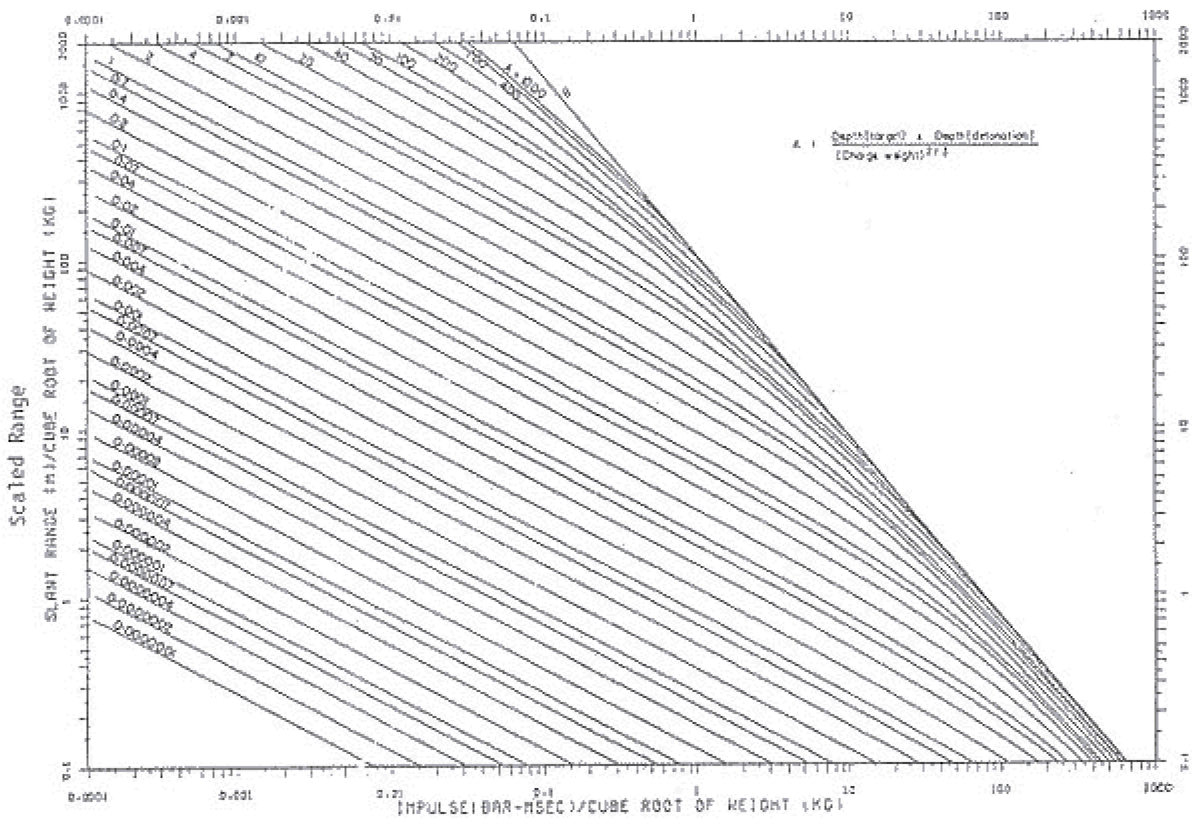

Figure 6.2.-Curves for calculating lethal range from impulse (from Hill 1978 after Yelverton et al. 1975).

EXAMPLE CALCULATION

For instructive purposes Wright (1982) provides the following sample calculation based on Hill's (1978) model.

What is the lethal range (50% mortality) for a 5 kg charge, detonated at a depth of 5 m? The fish in the area are Pacific herring Clupea harengus pallasii weighing 300 g, feeding on zooplankton at depths shallower than 10 m.

Weight of target fish = 300 g
Depth of target fish = 10 m
Depth of detonation = 5 m
Weight of charge = 5 kg

1. From Figure 6.1, an impulse of 2.3 bar-msec causes 50% mortality to 300 g fish;
2. The scaled impulse is calculated

$$\frac{\text{impulse}}{(\text{weight of charge})^{1/3}} = \frac{2.3}{5^{1/3}} = 1.35$$

3. Calculate the parameter 'A' using 10 m as the target depth This is a worst case since fish at shallow depth will experience a lower, less damaging impulse:

$$A = \frac{\text{target depth x detonation depth}}{(\text{charge weight})^{2/3}} = \frac{10 \times 5}{5^{2/3}} = 17.1$$

   Therefore, we use the curve for A = 20 in Figure 6.2.

4. Using the curve A = 20 in Figure 6.2 the scaled range corresponding to a scaled impulse of 1.35 will be 48.
5. Lethal range is given by:

$$R_1 = \text{scaled range x charge weight}^{1/3}$$
$$= 48 \times 5^{1/3} = 82.1 \text{ m}$$

Thus, 50% of all 300 g Pacific herring at depths of 10 m and at 82.1 m from the explosion will be killed outright.

Table 6.9 lists those factors which potentially influence fish mortality modeling. Development of a precise model would add little to the accuracy of mortality predictions, since fish community structure (species specific mortality), precise fish location in the water column and size would not be known with any accuracy. At best, a "worst case" impact assessment provides a conservative prediction of mortality. As such, the impulse or energy flux density models may be adequate for those purposes.

Table 6.9.- Parameters that can affect fish mortality making precise predictions of mortality difficult (From Keevin (1995)).

Biological Parameters

1. Depth of fish
2. Weight of fish
3. Species specific mortality

Environmental Parameters

1. Air-water roughness
2. Water-bottom roughness
3. Water/bottom acoustic impedance (bottom type)
4. Water temperature

Explosive Parameters

1. Depth of explosive
2. Relative bulk strength of explosive
3. Surface, mid-column, or drillhole shot
4. Pressure reduction from confined shot

Data Acquisition Parameters

1. Accuracy of pressure transducers and recording equipment
2. Pressure wave processing techniques
3. Standardization of pressure waveform calculations

MITIGATION TECHNIQUES TO PROTECT FISH FROM UNDERWATER EXPLOSIONS

Mitigation techniques are described in detail in Chapter 8.

CHAPTER 7

THE ENVIRONMENTAL EFFECTS OF UNDERWATER EXPLOSIONS: MARINE MAMMALS

INTRODUCTION

In mammals, gas containing organs (e.g., lungs, intestinal tract) are most affected by underwater detonation of explosives (Cameron, Short and Wakeley 1943; Clark and Ward 1943). Hill (1978) and Ketten (1995) provide the most recent reviews of existing literature.

INJURY AND MORTALITY OF MARINE MAMMALS EXPOSED TO UNDERWATER EXPLOSIONS

The potential for marine mammal mortality has been documented in the scientific literature. Fitch and Young (1948) indicated that on at least three occasions California sea lions (*Zalophus californianus*) were killed by underwater explosions used in geophysical survey work. California grey whales (*Rhachianects glaucus)* were seemingly unaffected and were not even frightened from the area. No information was provided on the location of the charge (open water or jet shot), size of the charge, or distance from the charge. Fur seals were reportedly killed by an 11.4 kg dynamite charge exploded 23 m away (H. F. Hanson, in Wright 1982). Reiter (1981) reported without further details that "there was evidence of [fur] seals....killed from concussion in the immediate area of demolition" when a grounded ship was broken up by about 454 kg of explosives.

Sea otter studies done in association with underground nuclear tests have provided data on the susceptibility of marine mammals to shock waves. Wright (1971) reported that sea otters (*Enhydra lutris*)were injured by pressures of 100 psi (0.69 MPa) and killed outright by 300 psi (2.07 MPa).

Richmond et al. (1973) and Yelverton et al. (1973) conducted a series of tests to assess the effects of underwater explosions on injury using sheep, dogs, and monkeys. Based on the results of their studies, Yelverton et al. (1993) developed underwater-blast criteria for aquatic and marine mammals (Table 7.1). An impulse of 40 psi-msec (275.8 Pa-s) would result in a high incidence of moderately severe immersion-bast injuries including a high probability of eardrum rupture. They suggested at that impulse the animals should recover on their own. An impulse of 20 psi-msec (137.9 Pa-s) would cause slight blast injuries and a high incidence of eardrum rupture. An impulse of 5 psi-msec (34.5 Pa-s) should not cause any injury and can be considered a safe level for mammals.

Richmond et al. (1973) also ran a series of tests with dogs beneath the surface to evaluate eardrum rupture. A probit analysis of the data yielded an impulse of 22.6 psi-msec (155.8 Pa-s) for 50% eardrum rupture. Yelverton and Richmond suggested that impulse (integral pat) in the underwater blast wave was the parameter that governed biological damage and not peak pressure of energy.

Table 7.1. Underwater-blast damage criteria for mammals diving beneath the water surface (From Yelverton et al. 1973).

Impulse		Criteria
psi-msec	kPa-sec	
40	275.8	No mortality. High incidence of moderately severe blast injuries including eardrum rupture. Animals should recover on their own.
20	137.9	High incidence of slight blast injuries including eardrum rupture. Animals would recover on their own.
10	69.0	Low incidence of trivial blast injuries. No eardrum ruptures.
5	34.5	Safe level. No injuries.

Young (1991) developed equations to estimate marine mammal safe ranges based on experiments with land mammals, presumably Richmond et al. (1973) and Yelverton et al. (1973). Injury was related to the response of air cavities, such as the lungs and bubbles in the intestines, to the shock wave. The estimated mammal safe ranges were based on absence of injury. Young (1991) suggested that the following marine mammal safe ranges (Table 7.2) be used for preliminary planning purposes. He suggested that the equations are technically correct but they do not cover all possible conditions or marine environments.

Table 7.2. Marine mammal safety zone range calculations (From Young 1991)

ENGLISH MEASUREMENT

Calf Porpoise, 200-ft d_w	$R_{ep} = 578\ W^{0.28}$
Adult Porpoise, 200-ft d_w	$R_{ap} = 434\ W^{0.28}$
20-ft Whale, 200-ft d_w	$R_w = 327\ W^{0.28}$

R = Range in feet
W = Weight of explosive in pounds
d_w = Depth of burst in feet

METRIC MEASUREMENTS (Conversions)

Calf Porpoise, 61.0-meters d_w	R_{ep} (m) $= 220\ W^{0.28}$ (kg)
Adult Porpoise, 61.0-meters d_w	R_{ap}(m) $= 165\ W^{0.28}$(kg)
20-ft Whale, 61.0-meters d_w	R_w (m) $= 124\ W^{0.28}$ (kg)

R = Range in meters
W = Weight of explosive in kg
d_w = Depth of burst in meters

Hill (1978) developed a model to predict lethal ranges for marine mammals based on data in Yelverton et al. (1975). The model has been reproduced in Wright (1982) and has been reproduced here. Hill (1978) indicated that the model Will "underestimate lethal ranges if the water depth is shallow (less than five times either the detonation depth or target depth, whichever is greater), and the bottom is rocky. In cases 1lke this, there may be a considerable bottom-reflected shock wave which will increase the impulse at any point. If the charge is to be detonated under thick ice, a positive rather than negative surface-reflected wave may result. Once again, this increases the impulse and, in turn, the lethal range. Under these

conditions, the calculated lethal ranges or safe distance should be doubled to ensure a conservative safety margin."

To use Hill's model to calculate lethal ranges or safe distance, the following information is required:

1. depth of the target mammal;
2. depth of detonation of the charge, and
3. weight of the charge.

To determine the range, the following steps are required:

1. Determine the impulse (I) corresponding to the degree of protection required for mammals from Table 7.1.
2. Calculate the scaled impulse by dividing the impulse found in Step 1 by the cube root of the charge weight.

   $(I_{sc} = I/wt^{1/3})$

3. Calculate parameter 'A', which is derived from the depth of the target fish or marine mammal, the depth of the detonation and the charge weight such that:

$$A = \frac{\text{target depth (m) x detonation depth (m)}}{(\text{charge weight (kg)})^{2/3}}$$

4. From Figure 7.1 find the best-fit curve to the calculated value of 'A' and using this curve, determine the value of the Scaled Range (R_{sc}) corresponding to the Scaled Impulse (I_{sc}) determined in Step 2.
5. Calculate the range (R) in meters by multiplying the Scaled Range by cube root of the charge weight.

   $R(m) = R_{sc} \text{ x charge wt}^{1/3}$

EXAMPLE CALCULATION

For instructive purposes Hill (1978) provides the following sample calculation.

What is the safe distance from a 5 kg charge detonated at a depth of 5 m for ringed seals? We wish to ensure that no harm is done to these animals by the explosion. Noting that the seals are feeding on small crustacea, and assuming that these are concentrated at depths less than 25 m, we can calculate the safe distance as follows:

1. According to Table 7.1, 0.34 bar-msec is a completely safe impulse level for submerged mammals;
2. The scaled impulse is calculated:

   $0.34/s^{1/3} = 0.2$

3. The quantity 'A' is calculated:

   $A = (5 \text{ x } 25)/5^{2/3} = 42.7$

4. Using the curve for A =40 in Figure 7.1, we find that a scaled range of 210 corresponds to a scaled impulse of 0.2. Therefore, the safe distance is given by :

$$R_S = 210 \times 5^{1/3} = 359 \text{ m}$$

Provided the charge is detonated at least 359 m from the seals, there should be no risk of damage.

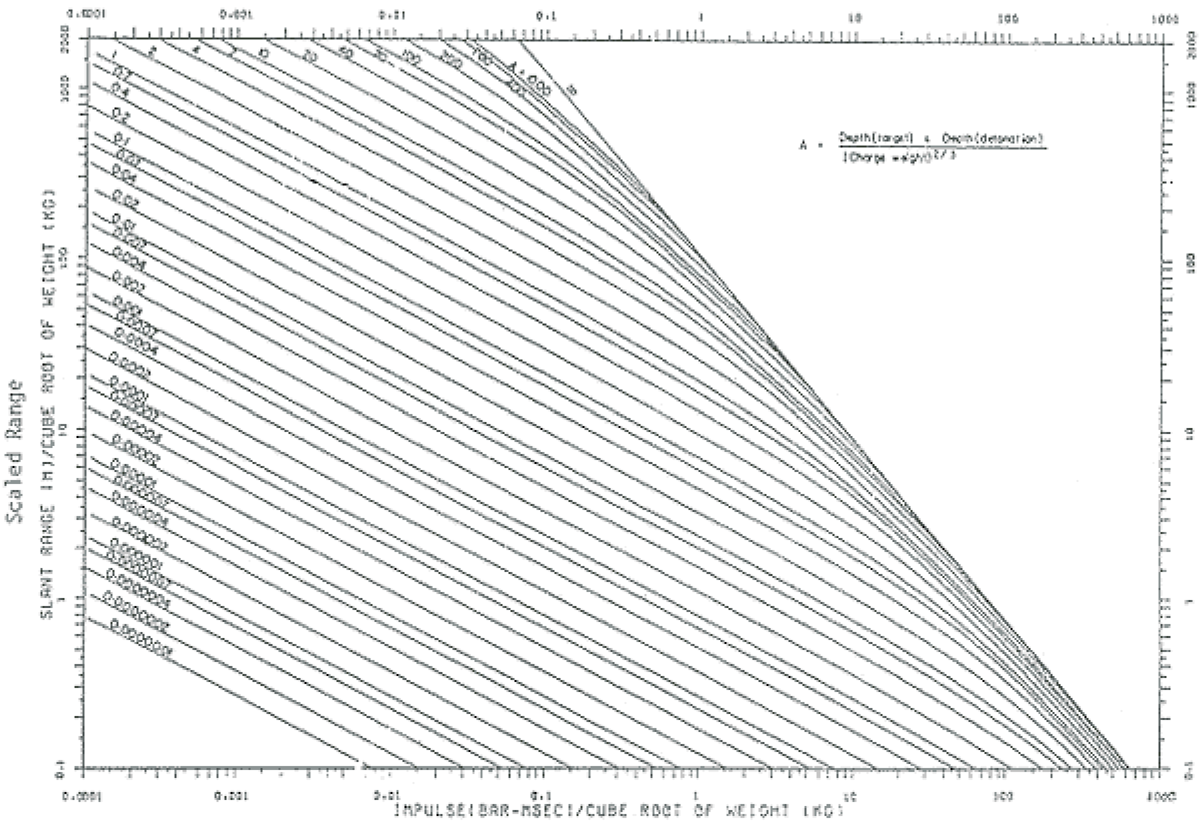

Figure 7.1.-Curves for calculating lethal range from impulse (From Hill 1978 after Yelverton et al. 1975).

Ketten (1995) suggested that for submerged terrestrial mammals, lethal injuries occurred at overpressures > 55 kPa and minimal injury limits coincided with overpressures of 0.5 to 1 kPa. These values seem very conservative when compared with Richmond et al. (1973) and Yelverton et al. (1973). For example, Richmond et al. (1973) found no internal damage in sheep exposed to 612 kPa from a 0.5 lb (225 g) charge of Pentolite at 10 ft (3.0 m) depth on sheep at 1 ft (305 mm) depth, 110 ft (33.5 m) from explosion. In addition, they found no ear damage in dogs with theirs at 1 ft depths (305 mm), exposed to 1.478 kPa from a 1ob (454 g(charge of TNT dtonated at 10 ft (3.0 m) depth, 60 ft (18.3 m) from the subjects.

BEHAVIORAL EFFECTS OF UNDERWATER BLASTING ON MARINE MAMMALS

There is little published information on the behavioral effects of underwater blasting on marine mammals. Todd et al. (1996) found that humpback whales (Megaptera novaeangliae) showed little behavioral reaction to construction detonations in terms of decreased residency, overall movement, or general behavior.

However, they found increased entrapment of humpbacks in fishing gear. Exposure to the construction explosions may have affected the hearing threshold of humpbacks, thus decreasing their ability to use net-produced acoustic cues to avoid net collisions. The probability of an entrapment occurring within 2 days or less of an explosion was 0.38, which was significantly greater than the calculated rate of 0.077 for entrapments occurring outside of a 2-day lag (z test of independent probabilities, $p < 0.0001$).

MITIGATION TECHNIQUES TO PROTECT MARINE MAMMALS FROM UNDERWATER EXPLOSIONS

Mitigation techniques described for fish are also applicable to marine mammals (see Chapter 8). Any attempt to reduce the pressure waveform will reduce the potential kill zone of marine mammals.

As with sea turtles, the simplest method to protect marine mammals from underwater explosions is to avoid periods when they are in the blasting zone. Avoidance of marine mammals can be achieved in two manners. Depending on location, there may be time periods when they are not in the project area due to their life history characteristics (e.g. migration patterns). This can be determined by coordination with the state natural resource agency or National Marine Fisheries Service. Blasting can be planned during time periods of low marine mammal abundance. If marine mammals are potentially in the area during blasting, an aerial survey using a light plane or helicopter can be conducted prior to detonation. If they are observed in the project area, blasting can be halted until they move out of a pre-determined blast zone.

An example of the above strategy is in place for explosive removal of oil and gas structures in state and federal waters of the Gulf of Mexico (Gitschlag 1990). For at least 48 hr prior to detonation, National Marine Fisheries Service observers watch for marine from the surface. Helicopter aerial surveys within a mile radius of the removal site are conducted 30 min prior to and after detonation (Gitschlag and Herczeg 1994). If marine mammals are observed, detonations are delayed until they have left the area.

"Seal bombs" and shell crackers have been used to "scare" marine mammals from the blast zone prior to detonating the large explosion. They have been used in attempts to prevent harbor seals, sea lions and other mammals from feeding on fish (e.g., Mate and Harvey 1987). These pyrotechnic devices expose the animals to sharp noise pulses of varying intensities. Seal bombs explode a few meters below the surface. Shell crackers fired from shotguns and several types of smaller pyrotechnics fired from pistols can explode above, at or below the surface. The general consensus from experience with these devices on the U.S. west coast is that, when first used, they startle the animals and often induce them to move away from feeding areas temporarily. However, the avoidance response wanes when the animals learn that the noise pulses are not harmful. Thereafter, some seals tolerate quite intense underwater sound in order to gain access to food (Mate and Harvey 1987).

There is a potential for marine mammal mortality resulting from the use of "seal bombs" as repelling charges. A similar device killed a human diver when it exploded approximately 0.3 m from his head (Hirsch and Ommaya 1972). Myrick et al. (1990) concluded that one Class-C device will cause injury when detonated within 0.5-0.6 m of a dolphin. They estimate a safe standoff distance of 4 m or more, depending on explosive type and depth.

CHAPTER 8

MITIGATING THE ADVERSE ENVIRONMENTAL EFFECTS OF UNDERWATER EXPLOSIONS ON FISH

INTRODUCTION

Development of effective mitigation strategies requires two components: a working knowledge of explosives and their impacts; and information on current mitigation techniques related to explosives, well grounded in practice theory. However, this is difficult because information about explosives and mitigative measures is often not widely accessible (reports, symposium proceedings, obscure scientific publications). The purpose of this chapter is to review natural resource agency mitigation policies; compare recommendations to available scientific literature on underwater explosive effects; and, develop a series of generic mitigation recommendations which will be useful to both natural resource planners and the blaster in developing strategies to reduce adverse effects of explosive use in aquatic ecosystems. This review is based on a recent publication by Keevin (In press) reviewing state natural resource agency mitigation policies.

A questionnaire was sent to fish and wildlife agency directors in each state to determine current agency policies on the use of explosives for legitimate purposes within waters under their jurisdiction (Keevin In press). Natural resource agencies were asked the following question concerning mitigation requirements within their state:

> "Does your agency require a person/company to apply mitigative techniques to reduce the potential for mortality to aquatic life during underwater blasting? If so, what mitigative techniques are required?"

In addition, the Canadian Department of Fisheries and Oceans' draft national guidelines, "Guidelines for the Use of Explosives in Canadian Fisheries Waters", were also reviewed since they provide mitigation recommendations for the use of explosives underwater.

Seventeen mitigation measures sere identified and are summarized in Table 8.1. They fall into three general categories: 1) review of the explosive design and provide mitigation recommendations based on that design; 2) evaluation of the potential impact and mitigative recommendations based on biological considerations; and, 3) evaluation of potential impact and require physical measures (e.g., bubble curtains, physical barriers, etc.) to minimize impacts. Each mitigation recommendation is reviewed based on existing literature and/or the physics of explosions. Although the mitigation recommendations were developed for fish, they are applicable to any organisms (e.g., marine mammals, sea turtles, etc.). However, specific mitigation recommendations are provided for non-fish species within their respective chapters.

Table 8.1.- Summary of State Natural Resource Agency Responses. (From Keevin (In press))

	AL	AK	AZ	AR	CA	CO	CT	DE	FL	GA
BLASTING DESIGN										
Agency Review	--	Y	--	--	--	--	--	--	--	--
Charge Type	--	--	--	--	--	--	--	--	--	--
Charge Weight	--	Y	--	--	Y	--	--	--	--	--
Shaped Charges	--	--	--	--	--	--	--	--	--	--
Delays	--	Y	--	--	--	--	--	--	--	--
Decking	--	--	--	--	--	--	--	--	--	--
Stemming	--	--	--	--	--	--	--	--	--	--
BIOLOGICAL CRITERIA										
Mortality Models	--	Y	--	--	--	--	--	--	--	--
Observers	Y	Y	--	Y	Y	--	Y	--	--	--
Compensation	Y	--	--	--	--	--	--	--	--	--
Sampling	--	--	--	--	Y	--	--	--	--	--
Seasonal Restrict	--	Y	--	--	--	--	Y	--	--	--
PHYSICAL MITIGATION FEATURES										
Repelling Charges	--	N	--	--	--	--	--	--	--	--
Noise	--		- -	Y	--	--	--	--	--	--
Bubble Curtain	--	N	--	--	--	--	--	--	--	--
Physical Barriers	--	--	--	--	--	--	Y	--	--	--

	HI	ID	IL	IN	IA	KS	KY	LA	ME	MD
BLASTING DESIGN										
Agency Review	Y	--	--	--	--	--	--	--	--	Y
Charge Type	Y	--	--	--	--	--	--	--	--	--
Charge Weight	Y	--	--	--	--	--	--	Y	--	Y
Shaped Charges	--	--	--	--	--	--	--	--	--	--
Delays	--	--	--	--	--	--	--	--	--	--
Decking	--	--	--	--	--	--	--	--	--	--
Stemming	--	--	--	--	--	--	--	--	--	Y
BIOLOGICAL CRITERIA										
Mortality Models	--	--	--	--	--	--	--	--	--	--
Observers	Y	--	--	Y	--	--	--	Y	Y	Y
Compensation	--	--	--	Y	--	--	Y	Y	--	Y
Sampling	--	--	--	--	--	--	--	--	--	Y
Seasonal Restrict	Y	--	Y	Y	--	--	--	Y	Y	Y
PHYSICAL MITIGATION FEATURES										
Repelling Charges	--	--	Y	--	--	--	--	--	--	--
Noise	--	--	Y	--	--	--	--	--	--	--
Bubble Curtain	--	--	--	--	--	--	--	--	--	--
Physical Barriers	--	--	---	Y	--	--	--	--	--	--

	MA	MI	MN	MS	MO	MT	NE	NV	NH	NJ
BLASTING DESIGN										
Agency Review	Y	--	--	Y	--	--	--	--	--	--
Charge Type	Y	--	--	--	--	--	--	--	--	--
Charge Weight	--	--	--	Y	--	--	--	--	--	--
Shaped Charges	--	--	--	--	--	--	--	--	--	--
Delays	Y	--	--	--	--	--	--	--	--	--
Decking	--	--	--	--	--	--	--	--	--	--
Stemming	--	--	--	--	--	--	--	--	--	--
BIOLOGICAL CRITERIA										
Mortality Models	--	--	--	--	--	--	--	--	--	--
Observers	--	--	--	Y	Y	--	--	--	--	Y
Compensation	--	--	--	--	--	--	--	--	--	--
Sampling	Y	--	--	--	--	--	--	--	--	--
Seasonal Restrict	--	Y	--	--	Y	--	--	--	Y	Y
PHYSICAL MITIGATION FEATURES										
Repelling Charges	--	--	--	--	--	--	--	--	--	Y
Noise	--	--	--	--	--	--	--	--	--	--
Bubble Curtain	--	--	--	--	--	--	--	--	--	Y
Physical Barriers	--	--	--	--	--	--	--	--	--	--

	NM	NY	NC	ND	OH	OK	OR	PA	RI	SC
BLASTING DESIGN										
Agency Review	--	--	--	Y	--	--	Y	Y	--	--
Charge Type	--	--	--	--	--	--	--	--	--	--
Charge Weight	--	--	--	--	--	--	--	--	Y	--
Shaped Charges	--	--	--	--	--	--	--	--	--	--
Delays	--	--	--	--	--	--	Y	--	--	--
Decking	--	--	--	--	--	--	--	--	--	--
Stemming	--	--	--	--	--	--	--	--	--	--
BIOLOGICAL CRITERIA										
Mortality Models	--	--	--	--	--	--	--	--	--	--
Observers	--	--	--	Y	Y	--	Y	--	--	--
Compensation	--	--	Y	Y	Y	Y	Y	Y	--	--
Sampling	--	--	--	--	--	--	Y	--	--	--
Seasonal Restrict	--	Y	Y	--	--	--	Y	Y	Y	--
PHYSICAL MITIGATION FEATURES										
Repelling Charges	--	--	--	--	--	--	--	--	Y	--
Noise	--	--	--	--	--	--	--	--	Y	--
Bubble Curtain	--	--	--	--	--	--	Y	--	--	--
Physical Barriers	--	Y	--	--	--	--	--	--	--	--

	SD	TN	TX	UT	VT	VA	WA	WV	WI	WY
BLASTING DESIGN										
Agency Review	--	--	--	--	--	--	--	--	--	--
Charge Type	--	--	--	--	--	--	--	--	--	--
Charge Weight	--	--	Y	--	--	--	Y	--	--	--
Shaped Charges	--	--	--	--	--	--	--	--	--	--
Delays	--	--	--	--	--	--	Y	--	--	--
Decking	--	--	--	--	--	--	--	--	--	--
Stemming	--	--	Y	--	--	--	--	--	--	--
BIOLOGICAL CRITERIA										
Mortality Models	--	--	--	--	--	--	--	--	--	--
Observers	--	Y	Y	--	--	Y	Y	Y	Y	--
Compensation	--	--	Y	Y	--	--	Y	Y	Y	--
Sampling	--	Y	--	--	Y	--	Y	--	--	--
Seasonal Restrict	--	--	Y	--	Y	Y	Y	Y	Y	--
PHYSICAL MITIGATION FEATURES										
Repelling Charges	--	--	N	--	--	--	Y	--	--	--
Noise	--	--	Y	--	--	--	--	--	--	--
Bubble Curtain	--	--	--	--	--	--	Y	--	--	--
Physical Barriers	--	--	Y	--	--	--	--	--	--	--

DEVELOPMENT OF MITIGATIVE STRATEGIES: THE BLASTING DESIGN

Agency Review of Blasting Design. Eight states responded that the blaster was required to submit a detailed blasting design for agency review prior to approval. The Canadian Department of Fisheries and Oceans also requires detailed blasting design information as a permit requirement.

Review prior to implementation of a project can be very effective in reducing impacts. The first step in the review process should be to determine if there is a need for use of explosives. Obviously, the best way to mitigate impacts of explosives is to avoid or minimize their use. The Oregon Department of Fish and Wildlife's blasting permit application requests information on alternatives to in-water blasting and for an analysis of their practicability. In a harbor project, the Massachusetts Department of Environmental Protection required the use of a mechanical breaker until there was a loss of efficiency, before blasting rock. Likewise, for seismic programs, the Mississippi Department of Environmental Quality indicated that although there was no specific language in their rules and regulations prohibiting the use of explosives as an energy source, "... the Commission would not look fondly on issuing a permit of that nature, especially since less invasive energy sources are currently available."

The second step in the review process should be a thorough review of the explosive design. A good explosive design (i.e., size of charges, use of shaped charges, stemming, decking, etc.) can help reduce adverse impacts to the aquatic environment. For example, a blasting cap, or cap and primer, is preferable from an environmental protection perspective over detonating cord to initiate an underwater explosive. This is because a blasting cap adds little to the magnitude of an explosion while detonating cord has an associated kill radius that extends along the cord from the firing mechanism to the explosive being detonated. Metzer and Shafland (1986) found that five species of experimental fish stationed within 7 m of a single strand of detonating cord (10.63 g PENTA/m) were killed instantly upon detonation. Use of detonating cord rather than a blasting cap (and possibly a primer charge) produces a cylinder of mortality with a 14 m diameter.

In conclusion, an agency requirement to provide detailed blast design information and to have a pre-project review meeting with the blasting company can be an extremely effective mitigation tool. Regulatory agencies can hamper the progress of initially approved programs. Projects can be delayed or contractual issues may arise, if regulatory agencies require approval of individual shots. Should the evaluation be slowed or the shot not be approved, the-blaster is revising the program outside of contractual obligations. Regulators offer the greatest aid when they provide operational review to some established limit, which may be revised, as the work demands through a specified procedure. The purpose of the regulation should be to remain within bounds of a reproducible, objective, environmental test.

Charge Type. Two respondents make recommendations concerning the type of explosive. The Massachusetts Department of Environmental Management required "the use of low-velocity explosives" in a dredging project at Cohasset Harbor. The rational for this approach is "probably" based on research (Baldwin 1954; Ferguson 1962; Fry and Cox 1953; Hubbs and Rechnitzer 1952) which indicated that black powder, a low detonation velocity explosive, had little effect on fish. Detonation velocity (DV) is the rate at which a blasting agent ignites. It ranges from about 1,650 to 7,650 m/s for products used commercially today (Dick et al. 1993a). Hubbs and Rechnitzer (1952) found that in marine fish species tested, the lethal threshold peak pressure from dynamite (DV = approximately 17,000 m/s) explosions varied from 276 to 483 kPa. Peak pressures from slow burning black powder (DV = 1,709 m/s), producing pressures as high as 855 to 1,103 kPa, did not kill caged fishes. Based on the findings of Hubbs and Rechnitzer (1952), Teleki and Chamberlain (1978) concluded that the lethality of an explosive is directly related to its detonation velocity. They suggested that the more rapid the detonation velocity the more abrupt was the resultant hydraulic pressure gradient and the more difficulty fish had adjusting to the pressure changes. They felt that a knowledge of the detonation velocity is critical to a true understanding of the impact of blasting on fish.

Use of black powder or gunpowder, widely used in early seismic exploration studies, has been largely discontinued due to hazardous handling properties and poor quality of seismographic records (Lipton et al. 1985b). Black powder produces a pressure waveform that is unlike other commercially available high explosives currently in use. It has a slow rise time, low amplitude, and long frequency when compared to high explosives which have an abrupt rise time, high amplitude, and short frequency. Keevin (1995) compared mortality of bluegill (Loomis macrochirus) exposed to three high-explosives types (T-100 Two Component, Pellite, and Apex 260) spanning the range of detonation velocities within commercially available explosives. Using equivalent weights of explosives, there was no significant difference in mortality curves based on distance from the explosive charge. This suggests that detonation velocity of commercially available explosives, recognizing that black powder deflagrates, is not an important factor in fish mortality.

The use of a linear charge, rather than a point-source explosive, during seismic exploration, may reduce fish mortality. Faulk and Lawrence (1973) and Mobil Oil (1984) found that the lethal range for linear-format explosives (e.g., detonating cords) is less than that of point source detonations for similar charge strength. Imperial Chemical Industries Ltd. (1968) reported that a 30 m length of "Aquaflex" containing 0.68 kg of explosive detonated 9 m below the water surface will produce a seismic record comparable in quality to that secured from a conventional 23 kg charge. Munday et al. (1986) suggested that the question that remains to be answered is how the relative lethality of the shock waves from linear explosives differs from point source detonations. They indicate the need for research involving the exposure of caged fish at different distances from linear charges. Munday et al (1986) note that measurement and analysis of the waveform "signature" generated by particular explosives should be an essential component of any such studies.

Canadian guidelines require that: "No explosive may be used that produces, or is likely to produce, an instantaneous pressure change greater than 100 kPa at a distance greater than 10 meters from the point of detonation." In order to meet this requirement, both the type of explosive and charge weight would have to be carefully evaluated. In an underwater blasting project for a natural gas utility crossing the Nipigon and Winnipeg rivers, McAnuff et al. (1994) chose an explosive product that was resistant to sympathetic detonation to comply with this guideline. Depth of the blast hole collar, and the length and gradation of stemming, also had to be carefully chosen.

Charge Weight. Nine respondents made recommendations concerning the charge weight of explosive. Reducing the charge size will reduce the amount of energy released into the water column. Blasters generally use developed experience, general formulae, or commercial computer programs to determine charge weight to accomplish a particular task. However, these procedures do not directly provide information specific to local conditions (e.g., local geology, rock hardness, concrete reinforcement, structural integrity). A limited testing program can often be employed to determine the minimum charge size to accomplish the required work, thereby minimizing environmental effects.

Doubling the explosive charge weight does not double the pressure. For deep shots, the peak pressure is approximately proportional to the cube root of explosive weight (Cole 1948). At 4 m distance, a 1 kg charge of TNT should produce 10.9 MPa peak pressure. A 2 kg shot, given the 1 kg charge pressure, scales to 14.2 MPa for the same 4 m distance. It would be necessary to increase the charge weight to 8 kg to produce a peak pressure of 23.9 MPa.

Shaped Charges. The term "shaped charge" refers to surface placement of explosives which have a preferred volumetric geometry or are formed with a lined or unlined cavity in the end opposite the initiation point. The detonating explosive progressively shatters the liner, focusing it into a directional high-velocity jet of particles. This jet has tremendous penetrating ability. Shaped charges can provide a fairly precise cutting tool in demolition work that can be used to weaken or destroy key structural points (Skinner et al. 1973). No respondents recommended use of shaped charges as a mitigation technique. Testing has not been conducted to determine if shaped charges produce less pressure impact to the environment. However, if blast energy is focused in such a way that the explosive is doing more "work", then less shock energy may be transmitted to the water column as compared to other surficially placed explosives. Also, shaped charges are used to do precise work which may reduce the total weight of explosives employed when compared to other explosive techniques.

Delays. Large explosive charges can be broken into a series of smaller charges by use of timing delays. For example, demolition of a bridge pier requires drilling numerous shot holes that are then filled with explosives. Shot holes can be detonated simultaneously or in succession, with a time interval between detonation of each shot hole or groups of shot holes. The greater the weight of explosives shot instantaneously, the greater the intensity of the shock wave and the greater the area of effect (Tansey 1980).

Delay blasting caps or series delays can be used to achieve delay periods between successive detonation of shot holes. Blasting caps with different delay periods are available; delay periods range from 25 msec (cap #1) to 1,125 msec (cap #20). During detonation, all caps are initiated simultaneously, but the larger the cap number, the longer it takes a filament inside the cap to burn before the charge is initiated. The use of delay caps effectively reduces each detonation to a series of small explosions. In the case where electric initiation is prohibited, series delays may be used, series delays detain the propagation of the ignited or detonated medium. Resulting blast overpressure levels are directly related to the

size of the charge for delay, rather than the summation of charges detonated in all holes (Munday et al. 1986).

There has been no field testing to determine the effectiveness of this technique in reducing aquatic mortality. However, if the pressure wave can be broken into a series of smaller waves that fish internal organs can dynamically respond to as a single event, then the technique should be effective in reducing mortality. Ogawa et al. (1976) conducted a laboratory experiment on the response time of fish to pressure. They reported that fish response time, measured as recovery from deformation, was on the order of 100 msec. In a pressure pulse repetition experiment, no increase in injuries was observed for pulse periods less than 100 msec. However, if it rose above 100 msec, the effect of pressure pulse repetitions on injuries could be detected. Limited field testing (Anonymous 1948) also suggests the importance of producing a repetitive pressure pulse that fish respond to as a single event. Explosions fired in succession extended the immediate lethal range and killed more fish. Based on what has been well researched, the effectiveness of delays in sequence and defining the minimum delay period that provides maximum protection, requires further examination.

Four states responded that delays were recommended as a mitigative technique. Canadian guidelines require the preparation of a mitigation plan that should include the following measure: "if multiple charges are required, time-delay detonation initiators (blasting caps) should be used to reduce the overall detonation to a series of discrete explosions." The Alberta Forestry, Lands and Wildlife Fisheries Habitat Protection Guideline No. 15 recommends "a minimum delay of 25 msec must be used, but a delay of 50 msec between successive charges is recommended; they also state that: "In underwater blasting, confined charges should be used."

Decking. Explosive charges can be "decked" within a bore hole. In this procedure, two or three charges are included in one hole separated by a non-explosive material. A longer delay is used for the lower charge than for the upper charge, causing the upper charge to detonate first, followed by the lower charge. In effect, decking produces results similar to time delays. As a result, overpressure levels are lower than if both charges were combined as a single shot (Munday et al. 1986). The effectiveness of this procedure in reducing environmental effects has not been evaluated; however, lower overpressures should reduce the kill radius.

No state fish and wildlife agency indicated that decking charges was a recommended mitigation procedure. Canadian guidelines require the preparation of a mitigation plan that should include the following measure: "if possible, large charges should be subdivided into a series of smaller charges (a procedure known as decking) using time-delay detonation initiators (blasting caps) to reduce the overall detonation to a series of smaller discrete detonations or explosions."

Stemming. Stemming is the use of a selected material, usually angular gravel or crushed stone, to fill a drill hole above the explosive. Stemming is commonly used by the blasting industry to contain the explosive force and increase the amount of work done on the surrounding strata (Konya and Davis 1978; Moxon et al. 1993). This technique decreases the amount of gas energy that is lost out of the drill hole and thus reduces the impact to the aquatic environment. Brinkmann (1990) has shown that approximately 50% of the explosive energy is lost if unrestricted venting is allowed to occur through the blasthole collar. Susanszky (1977) found, in a series of tests in the Danube River, that absolute values of pressures were decreased by an order of magnitude by using soil for stemming.

Konya and Davis (1978) conducted a series scaled down tests of a variety of stemming materials in a ballistic mortar with a long, roughened bore to simulate the collar of a blast hole. They found that highly spherical sand (wet or dry)

ejected even when loaded to the full bore length (1 m), whereas very angular limestone of similar grain size held at the same powder charge with as little as nine inches of stemming. They concluded that angularity appears to be the single most influential variable in maintaining the stemming material in the blast hole. Gordon and Niles (1990) noted that mud and drill cuttings were poor stemming materials and that angular material was the best materials since it arched and locked into the borehole wall when subjected to detonation pressure. They recommended that the optimum crushed rock particle size should be approximately 1/12 of the borehole diameter.

Two respondents indicated that stemming was recommended to reduce impacts. For example, a permit applicant conducting seismic testing in West Galveston Bay, Texas, proposed placing charges in shot holes and allowing approximately 30 days to pass before detonation to allow the shot hole walls to slough thus "packing" the holes. In response to the proposal, the Texas Parks and Wildlife Department indicated that "... continued loss of fisheries resources could require the packing of shotholes with small gravel or other appropriate material to reduce the changes of pressure." Canadian guidelines for use of explosives in fisheries waters provide for the possible use of stemming as a mitigation feature. "[T]he hole must be back-filled (stemmed) with sand or gravel to the level of the substrate/water interface or the hole collapsed to confine the force of the explosion to the formation being fractured."

DEVELOPMENT OF MITIGATIVE STRATEGIES: BIOLOGICAL CRITERIA

Individual Project Review. Although the question was not specifically asked, most states indicated that each proposed explosive-use project was evaluated on an individual basis. This represents a reasonable approach for evaluating the explosive use design, the existing fishery resources in the blast area, and the magnitude of impact. The agency can review existing fishery data for the blast area, or require a survey if none is available. This allows the agency to make rational decisions based on the quality of fishery (e.g., anadramous fish migrations, larval fish drift, endangered species). This approach also allows flexibility in developing mitigation plans based on the potential impact of each individual project.

Predictive Mortality Equations. An underwater explosion represents a single point of disturbance to the aquatic environment; thus, the mortality zone is generally restricted. A reactionary approach, one requiring stringent mandatory mitigative techniques without a preliminary assessment of impacts, would not be in the best interests of the blaster or the regulatory agency. Such an approach would not benefit the aquatic resources that a regulatory agency is required to protect. Based on predictive equations, the kill radius for an underwater explosion can be calculated prior to commencement of the project. Three such predictive models are available: the energy flux density model (Sakaguchi et al. 1976), the impulse strength model (Baxter et al. 1982; Hill 1978; Munday et al. 1986; Wright 1982; Yelverton et al. 1975), and the dynamical model (Wiley et al. 1981). A user-friendly computer program was developed by COASTLINE Environmental Services Ltd. (1986) that uses the impulse strength model (IBlast) and the energy flux density model (EBlast) to predict effects for both midwater charges and charges that are drilled and buried in rock substrate. Although there are problems associated with these models (Hempen and Keevin 1995; Keevin 1995), they do give an approximation of the potential fish kill radius of a given explosive charge. O'Keeffe (1984) and Young (1991) provide kill probability contours for various fish sizes and charge weights based on the predicted results obtained by the dynamical model.

Two factors need to be considered when estimating total fish mortality using mortality models. Midwater and open water models were developed using open water shot data, so they may be useful in evaluating open water seismic charges but will

overestimate mortality for shots confined within solid media (e.g., demolition shots). Physoclistous fish species (swim bladder attached to the circulatory system allowing slow change in bladder pressure) may be more sensitive to blast pressures than either physostomus species (swim bladder attached to the esophagus allowing quick release of air) or species with no airbladders (Teleki and Chamberlain 1978).

Explosives in open water, that are not contained completely by rigid structures, will produce both higher amplitude and higher frequency shock waves, than contained detonations. Thus, the use of blasting in structure demolition, when the explosives are enclosed within the structure being razed, should result in lower fish mortality than the same explosive detonated in open water. For example, "burning" a steel beam underwater with perimeter charges to sever it would cause higher mortality than the severance of a concrete pier using an explosive of the same weight and detonation velocity placed within the pier by drilling and stemming. The greater the shock energy is transmitted away from the water column through solid media, the lowering the capacity of the water-borne shock wave to cause mortality.

No state fish and wildlife agency currently uses fish mortality models in their pre-project assessment of impacts nor require applicants to submit potential fish kill radius data based on mathematical models. Alaska has used a fish mortality model as a predictive tool to protect marine diving mammals. Nevertheless, this simple planning procedure could give the natural resource agency valuable information concerning the potential magnitude of impact from the use of underwater explosives.

The Canadian guidelines for use of explosives in fisheries waters require the preparation of an environmental impact assessment which includes "the theoretical lethal range of the explosives to be used" based on equations provided in the guidelines. These calculations are made to determine if the explosive charge weight is likely to exceed guideline standards, an instantaneous pressure change greater than 100 kPa at a distance greater than 10 meters from the point of detonation.

The Alaska Department of Fish and Game has used IBlast (COASTLINE Environmental Services Ltd. 1986), in conjunction with mammalian injury data provided in Wright (1982) to set standards for maximum allowable impulse strengths to protect diving mammals during explosive channel excavation within St. George Harbor. They suggested an upper limit of 69 kPa/ms as measured at the mid-water-column depth 150 meters horizontal from the charge.

Observers. Twenty-two states and Canadian guidelines require pre-notification so that an agency representative may be present to assess blast impacts. As a result, the resource agency can better evaluate the magnitude of the impact. If fish mortality is considered excessive, an agency has the option of either halting blasting, requiring significant blasting revisions, requiring the use of mitigative techniques, or requiring monetary compensation for any fish killed. The Missouri Department of Conservation has successfully employed this technique on three recent projects, a lock and dam demolition project, removal of rock outcroppings considered hazardous to navigation, and intake channel construction. However, conservation agents did not find what they considered significant mortality levels from blasting on these Missouri projects.

Many agencies suggested that if high numbers of fish are killed, the applicant would be required to cease blasting or to provide appropriate mitigation. For example, in a project involving bedrock removal in the Potomac River using controlled blasting techniques, the Maryland Department of Natural Resources granted a permit with the condition that the applicant contact the agency "at least 24 hours prior to any day that blasting will be conducted so that an observer may be present." In addition, they noted that if "it is determined that excessive numbers of fish are being killed, the applicant may be required to stop blasting

and/or provide appropriate mitigation for fishery losses."

Compensation of Fishery Losses. Sixteen agencies have either required, or have provisions for, monetary compensation of fish losses based on replacement values developed by the American Fisheries Society (1982, 1992, 1993). Sometimes adjustments to replacement values are made to reflect unique circumstances or to include marine species. Monetary value may be based on: actual counts of dead fish; mathematical mortality models projecting fish kill levels; or actual testing programs. As part of their permitting authority, the Texas Parks and Wildlife Department (TPWD) required the applicant fund a testing program to gather mortality data to project possible impacts from a proposed 3-D seismographic survey in West Galveston Bay. It involved a series of tests using methods proposed for the survey. Using the test data, they projected what would be the total fish kill if the geophysical survey was carried to completion. A monetary value was then assigned using TPWD Guidelines. American Fisheries Society (1982) replacement values were supplemented with added recreational values for any sport fishes killed.

TPWD recognized society's need to conduct such survey work, by making provisions to allow a certain acceptable level of fish mortality without compensation. As an environmental cost of performing geophysical surveys for new oil and gas reserves, ten pounds of fish per 18 acres of surveyed area were deducted from the total projected fish kill. The total weight allowed (2,543 kg) for the entire area affected by the survey was distributed over each species and size class based on their proportion of the total kill weight.

If monetary compensation is based on counts of dead fish found floating at the surface, an agency must recognize that observed numbers do not represent the total fish kill. Incidental observations indicate that many dead fish do not surface (Brown and Smith 1972; Coker and Hollis 1950; Ferguson 1962; Fitch and Young 1948; Indrambarya 1949; Kearns and Boyd 1965; Knight 1907). The proportion of "floaters" to the actual number of fish killed has never been documented. For this reason, resource agencies should use a conservative approach and increase the monetary compensation by a predetermined factor (i.e., possibly 2 or 3 times the observed mortality). This approach would allow the contractor to continue work while the loss to the fishery resource is compensated.

Pre-Blast Sampling Surveys To Detect Fish Presence. Seven respondents recommended or required use of sonar surveys or other sampling techniques to establish presence of fish in the blast area prior to detonation. Monitoring allows detection of migratory populations near the blast site, thereby decreasing the potential risk of higher fish kills.

The Washington Department of Fisheries required the Seattle Engineering Department to contract for hydroacoustic surveys before bridge pier demolition in the Duwamish River to locate salmon in or around the project site. Results were then used to determine whether or not demolition could proceed (Gaia Northwest, Inc. 1990).

It appears that pre-blast surveys have limited value. Munday et al. (1986) showed that fish kill number could not be predicted consistently from pre-blast sonar surveys. Use of purse seining also proved to be only marginally effective in sampling resident populations even when fish schools were found by echo location. Kearns and Boyd (1965) reported that sonar surveys predicted fish kills only 36% of the time in seismic refraction studies off Vancouver Island. Purse seining was used to measure fish presence near a blasting operation in a shallow marine embayment, False Creek, B.C. (Nix and Chapman 1983). Although seine catches reflected week-to-week and month-to-month changes in fish presence, seining success was not closely correlated with fish kills resulting from single detonations. Munday et al. (1986) concluded that monitoring resident fish populations by both sonar surveys and purse seining is not a very reliable method for predicting mortalities from underwater

detonations even if the lethal range can be predetermined. Use of monitoring can identify day-to-day changes in resident fish presence, but precise constraints of monitoring techniques restrict their usefulness within the predicted lethal zone. On-site sampling, particularly hydroacoustic surveys, are useful in identifying periods of major fish migrations, periods when explosive use may need to be restricted by the natural resource agency.

Seasonal Restrictions on Blasting. Twenty-three respondents consider use of time limits during review of blasting proposals. Natural resource agencies are in the best position to know when potentially sensitive time periods occur in the life history of species of concern. Sensitive periods can include those associated with mass migrations, high larval fish abundance, and fish spawning. An agent can review the blast proposal and, based on the magnitude of the program, determine if time limitations are warranted.

The Oregon Department of Fish and Wildlife applies permit conditions that include restrictions on timing of in-water blasting "to prevent injury to fish and wildlife and their habitat, fish eggs or other aquatic life, as well as commercial and recreational fisheries....". The Department has developed guidelines outlining preferred work periods for each waterway, by region. This information is available to the blaster as part of Oregon Administrative Rules for In-Water Blasting Permits. There are provisions to allow the local fishery biologist latitude when a species of concern is not in the area during a proposed blasting period or if a species is present and not adequately protected by the timing guidelines.

Canadian guidelines for the use of explosives in fisheries waters require that "the project should be undertaken at the time of least biological activity or biological sensitivity. Proponents should consult with DFO Regional/Area Authorities to determine the appropriate timing."

DEVELOPMENT OF MITIGATIVE STRATEGIES: USE OF PHYSICAL MITIGATION FEATURES

Repelling Charges. Repelling charges are small explosive charges detonated to "scare" fish from the blasting zone just prior to detonation of a major explosive charge. For example, a demolition contractor, removing a reinforced concrete bridge pier with explosives, would first detonate a series of small repelling charges (e.g., 0.11-0.22 kg explosive charge, explosive boosters) encircling the pier, wait a predetermined time period, and then detonate the demolition charge. It is assumed that noise or pressure from the small charge will drive fish from the immediate area thereby reducing impacts from the much larger and potentially more-damaging main blast. The blasting industry recommends firing a "warning shot" to frighten fish out of an area before seismic exploration work is begun (Anonymous 1978). Blasting companies have used this technique in a "good faith effort" to mitigate potential damages to aquatic resources. It is quick, inexpensive, and does not require use of more sophisticated techniques.

Illinois, New Jersey, Rhode Island, and Washington, recommended use of repelling charges as a mitigation feature. Two respondents indicated that use of repelling charges was not acceptable. The Alaska Department of Fish and Game considered repelling charges to be ineffective and "potentially harmful to piscivorous fishes, marine mammals, and birds which are attracted to feed on fish that are stunned or wounded by the repelling charge." In response to an applicant's proposal to remove pilings from Pine Island Bayou and the Neches River, the Texas Parks and Wildlife Department recommended: "Do not attempt to scare fish away from the site by small charges of explosive. Use of boats or similar noisy operations may be employed."

Canadian guidelines require the preparation of a mitigation plan and suggests that the proponent should consider "detonation of small scaring charges, consisting of

detonator caps or short lengths of detonating cord, set off one minute before the main charge to scare fish away from the site." In response to the Canadian guidelines, McAnuff et al. (1994) detonated a submerged length of primacord or a blasting cap, both upstream and downstream of the blast zone, 30 to 60 seconds prior to the main blast during a gas utility crossing project on the Nipigon and Winnipeg rivers. They noted that on at least one occasion the "scare blast" contributed to fish mortality. In addition, the primacord or cap positioned on the upstream side of the blast tended to be carried downstream toward the main blast due to the strong currents in the river which could have resulted in a cutoff or an unplanned detonation of the main blast.

Incidental observations during blasting operations indicate that explosions are not effective in "scaring" fish from the blasting zone (Aplin 1947; Ferguson 1962; Fitch and Young 1948; Nix and Chapman 1985; Ross et al. 1985). For example, Ross et al. (1985) made three observations on the response of American sand lance (Ammodytes americanus) schools to the detonation of two parallel 25 m lengths of Aquaflex, an explosive cord. The sand lance were observed for a period of 30 s to 120 s before a blast and from 30 s to 60 s after. Observations were of large schools (1000's) swimming against the current. Movements up and down in the water column were observed in response to current surges, with the sand lance hugging the bottom. In response to a blast, all members of the school under observation altered course for approximately 1 to 2 s, before resuming their original orientation and movement patterns. There was no flight response.

A radio telemetry study of largemouth bass (Micropterus salmoides), channel catfish (Ictalurus punctatus), and flathead catfish (Pylodictis olivaris) also found that small charges were ineffective in moving fish (Keevin et al. 1997). Movement distances were used to estimate the proportions of fish which would theoretically move out of computed kill zones associated with detonation of large charges of high explosives. Table 8.2 gives the number of individuals that would have moved out of the kill zone based on their measured movement during repelling charge trials compared with theoretical mortality zones for a range of charge sizes that were calculated using IBLAST (COASTLINE Environmental Services Ltd. 1986). Largemouth bass (n=15) showed little response to repelling charges and none would have moved out of the kill zone calculated for any explosive size. Only two of six flathead catfish tested would have moved to a safe zone based on the kill radius calculated for the smallest theoretical blast weight. This charge size is smaller than would be used for demolition work, for example.

Table 8.2.- Movement of radio-tagged fish from kill zones based on their response at 5 min to repelling charges (see Table 8.3). Predicted kill zones are based on LD0% mortality for a range of charge weights. (From Keevin et al. (1997))

	Expected LD0% Mortality[1]				
Charge weight-explosive (kg)	4.5	11	23	34	45
Predicted mortality range (m)	31	37	42	45	47
	Number moving out of kill zone				
Largemouth bass (N=15)	0	0	0	0	0
Channel catfish (N=7)	2	2	2	2	1
Flathead catfish (N=6)	2	1	1	1	1

[1]Calculated using IBlast (Coastline Environmental Services Ltd. 1986)

Only one flathead catfish would have moved from the kill zone produced by a demolition blast. Two of seven channel catfish tested moved out of the kill zone. Study results are consistent with published observations of the response of fish schools to underwater explosions. Table 8.3 provides information on the species, weight, and habitat type during testing, and distance moved away from the 680 g repelling charge for each individual tested.

Fish mortality from repelling charges, a concern expressed by some natural resource agencies (Keevin, In press), has been documented by field observations (Nix and Chapman 1985; McAnuff et al. 1994). Draft "Guidelines for the Use of Explosives in Canadian Fisheries Waters" (Wright 1992) required the preparation of a mitigation plan and suggested that the proponent should consider "detonation of small scaring charges, consisting of detonator caps or short lengths of detonating cord, set off one minute before the main charge to scare fish away from the site." In response to conditions (based on draft Canadian guidelines) placed on a blasting project by the Ontario Ministry of Natural Resources, McAnuff et al. (1994) detonated a submerged length of primacord or a blasting cap, both upstream and downstream of the blast zone, 30 to 60 seconds prior to the main blast during a gas utility crossing project on the Nipigon and Winnipeg rivers. They noted that on at least one occasion the "scare blast" contributed to fish mortality. In addition, the primacord or cap positioned on the upstream side of the blast tended to be carried downstream toward the main blast due to the strong currents in the river which could have resulted in a cutoff or an unplanned detonation of the main blast. A final version of the Canadian guidelines (Wright, In press) no longer contain recommendations for the use of repelling charges.

Noise. Commercial fishermen have used noise to move fish into nets. Four respondents indicated that noise propagation was used or recommended as a mitigation technique. For example, during a rock removal project on the Arkansas River, the Arkansas Game and Fish Commission recommended that noise be used to repel fish from the blast area. The contractor employed a siren device to scare fish from the work area.

Table 8.3.- Weight (kg) and length (cm) of test fish, distance moved (m) in response to repelling charge, and habitat type of fish prior to testing. (From Keevin et al. (1997))

Largemouth bass

Fish #	Weight (kg)	Length (cm)	Distance Moved (m)	Habitat Type
49.600	1.0	38.6	0	Brushpile
48.510	1.3	43.2	6	cover
48.750	1.4	38.9	6	cover
49.790	0.9	39.4	3	cover
48.060	1.0	40.1	3	cover
48.580	1.0	38.1	0	open water
48.450	1.4	43.9	9	open water
49.270	1.3	42.2	9	open water
49.660	1.0	38.6	23	open water
49.460	1.4	45.0	18	open water, reeds
49.170	1.2	41.9	0	open water,cattails
49.130	1.4	44.5	0	shoreline, brush pile
49.700	1.0	40.1	0	shoreline, brush pile
49.100	1.4	42.9	0	open water, shallow
49.640	1.2	41.7	0	open water

Channel catfish

Fish #	Weight (kg)	Length (cm)	Distance Moved (m)	Habitat Type
49.060	2.2	57.4	9	open water
49.750	1.2	47.0	46	open water
49.150	2.4	62.5	0	open water
49.080	2.0	59.2	0	open water
48.200	1.1	49.8	66	open water
49.342	1.6	53.9	30	open water
49.040	2.2	57.6	23	open water

Flathead catfish

Fish #	Weight (kg)	Length (cm)	Distance Moved (m)	Habitat Type
49.442	1.6	49.4	23	shoreline
49.520	1.6	52.8	0	shoreline, cover
49.540	2.6	61.0	0	shoreline, cover
49.482	1.9	53.3	0	open water
48.625	1.7	50.0	36	open water
49.723	2.7	99.7	55	open water

Studies testing the effectiveness of a constant noise source to repel fish from a blasting area have focused on clupeids and salmonids. Dunning et al. (1992) found

that during daylight alewife (Alosa pseudoharengus) schooled and avoided: pulsed tones (500 ms pulses, 1,000 ms apart) of 110 and 125 kHz at or above 175 dB; a continuous tone of 125 kHz at 172 dB; and, pulsed broadband sound between 117 and 133 kHz at or above 157 dB. However, pulsed broadband sound at 163 dB was most effective. In contrast, alewives did not react as strongly to the broadband sound at night. At the Pickering Nuclear Generating Station on Lake Ontario, Haymes and Patrick (1986) used pneumatic poppers emitting low-frequency, high-intensity broadband sound, of frequencies between 20 and 1,000 Hz. They found this sound reduced by up to 99% the number of alewives entering an experimental structure. The effectiveness of pulsed, high-intensity broadband sound on species other than alewife is not known.

Knudsen et al. (1994) found that 10 Hz sound was an effective deterrent for downstream migrating Atlantic salmon smolt (Salmo salar) in a small river. In contrast, 150 Hz sound had no repelling effects. It is not known if fish can be moved a large enough distance from an explosive detonation to be out of the potential kill radius. This is an area which requires additional study. If effective, use of noise would be a low cost, "good faith" effort by the blaster to reduce impacts.

Bubble Curtain. A bubble curtain, also called an air curtain or air screen, is created by injecting compressed air into the water column. Bubble curtains are walls of bubbles rising from a bottom-resting bubbler manifold supplied with compressed air. Bubbler manifolds are typically constructed using rows of parallel pipes with small holes drilled along their length. The pipes are supplied with air from one or more distribution headers that equalize pressure to each pipe. Bubble curtains are effective in reducing pressures across the air bubble curtain (Strange 1963). Research has shown that a small fractional volume of air bubbles in water increases the compressability several orders of magnitude above that in bubble-free water, thereby greatly reducing the velocity and increasing attenuation of acoustic waves (Domenico 1982a). As a result, bubble curtains have been routinely used by demolition engineers to protect underwater structures from damage by underwater explosive shock waves (Domenico 1982b). Guidelines for such use are given in Langefors and Kihlstrom (1978).

Alaska, New Jersey, Oregon, and Washington require the use of bubble curtains or recommend it as a mitigative strategy. Canadian guidelines require the preparation of a mitigation plan and suggests that the proponent should consider "deployment of bubble curtains/air curtains to disrupt the shock wave." The Alaskan Department of Fish and Game indicated that: "Bubble curtains have been specified in the past but their ability to mitigate impacts to aquatic life is questionable and their use has been discontinued." The question of the bubble curtain's effectiveness in reducing mortality arose during the explosive removal of oil rig legs in Kachemak Bay during 1976. Mortality was observed outside the bubble curtain. However, the without bubble curtain condition was not tested and mortality would possibly have been much greater without the bubble curtain in operation. Design of the bubble curtain must be appropriate for the conditions to achieve effective mitigation.

Keevin et al. (In press) conducted small-scale, shallow-water field trials evaluating the effectiveness of an air bubble curtain in reducing explosive pressures and the associated fish kill radius of underwater explosions resulting from the detonation of a 2 kg high-explosive charge. One test limitation was that the bubble curtain did not completely enclose the water-column shot. The bubble curtain produced considerable reductions in peak pressure, impulse, and energy flux density and significant reductions in fish mortality (Table 8.4). Peak pressure reductions ranged from 99.4-87.5%. Impulse, calculated by integrating the first positive wave, showed reductions ranging from 89.8-80.7%. Energy flux density reductions ranged from 99.8-89.7% (Table 8.5). A significant reduction ($p < 0.05$) in bluegill (Lepomis macrochirus) mortality was observed when the bubble curtain

was in operation (Table 8.6). Mortality fell from 100%, without the bubble curtain, to 0% with the bubble curtain in operation, at all distances tested.

An air bubble curtain was found to be extremely effective in reducing fish mortality during explosive demolition of Locks and Dam 26 on the Mississippi River (Keevin et al. 1997). Mortality was lowered despite a large underwater explosion (886 kg total weight of 21-54 kg charges/delay), moderate water depth (10.1-11.6 m at the bubble curtain) and high current velocities (approximately 0.6 m/s). A significant reduction ($p < 0.05$) in mortality at 120 hr. at all distances tested, was found for bluegill with the bubble curtain in operation when compared to the without bubble curtain condition (Table 8.7). Total mortality (100%) was observed to 80.8 m from the blast without the bubble curtain. Mortality was observed at all nine distances tested and was still 58% at 117.4 m, the farthest distance tested. With the bubble curtain in operation, 19% mortality was observed at 19.8 m from the explosion. There was no explosion related mortality past 19.8 m, comparing the mortality at each distance with control mortality, when the bubble curtain was operating.

Table 8.4.- Pressure waveform values resulting from underwater detonation of a 2 kg charge of T-100 at 1.25 m depth without and with the use of a bubble curtain. Independent duplicate trials are reported. (From Keevin et al. (In press))

	Without Air Bubble Curtain				With Air Bubble Curtain				Control
	DISTANCE (Meters) FROM EXPLOSION								
	6.5	9.0	11.5	14.0	6.5	9.0	11.5	14.0	Control
SHOT 1									
Peak Pressure(kPa)	32,600	3,970	2,240	2,180	The 207 kPa peak pressure trigger setting on the oscilloscope was not exceeded on the 6.5 m transducer.				0
Impulse(Pa-s)[1]	1,230	384	279	207					0
Impulse (Pa-s)[2]	1,630	601	509	398					0
Energy Flux Density (J/m^2)	15,000	491	280	226					0
SHOT 2									
Peak Pressure(kPa)	21,700	4,630	2,610	2,170	302.0	224.00	234.00	272.0	0
Impulse(Pa-s)[1]	990	357	249	175	93.9	36.60	31.00	33.7	0
Impulse (Pa-s)[2]	1,100	512	404	314	164.0	39.00	48.10	46.1	0
(J/m^2)	6,000	346	226	115	11.1	7.62	9.79	11.9	0

[1]Impulse was calculated by integrating the pressure-time curve for first positive wave.
[2]Impulse calculated by the greatest difference of peak pressure to pressure low. Is the greatest strength of expansion which has the potential of worst air-filled organ damage.

Table 8.5.- Percent reduction in pressure waveform values with the air bubble curtain in operation. Value were calculated using pressure waveform data in Table 1 from the underwater detonation of a 2 kg charge of T-100 at 1.25 m depth without and with the use of a bubble curtain. (Modified from Keevin et al. (In press))

	DISTANCE (Meters) FROM EXPLOSION			
	6.5	9.0	11.5	14.0
SHOT 1[1]				
Peak Pressure(kPa)	99.4	94.8	91.0	87.5
SHOT 2				
Peak Pressure(kPa)	98.6	95.2	91.0	87.5
Impulse(Pa-s)[2]	85.1	89.7	87.6	80.7
Energy Flux Density (J/m^2)	99.8	97.8	95.7	89.7

[1]A value of 207 kPa was used as the peak pressure value for the air bubble curtain in operation. The oscilloscope was set to trigger at 207 kPa. However, this value was not exceeded. Since actual pressure waveforms were not available for shot 1, it was not possible to calculate impulse or energy flux density.

[2]Impulse was calculated by integrating the pressure-time curve for first positive wave.

Table 8.6.- Bluegill mortality based on live/dead counts (n=50 at each distance tested) resulting from underwater detonation of a 2 kg charge of T-100 at 1.25 m depth without and with the use of a bubble curtain. Independent duplicate trials are reported. (From Keevin et al. (In press))

	Without Air Bubble Curtain				With Air Bubble Curtain				Control
	DISTANCE (Meters) FROM EXPLOSION								
	6.5	9.0	11.5	14.0	6.5	9.0	11.5	14.0	--
SHOT 1									
Number Tested	50	50	50	50	50	50	50	50	50
96 hr Mortality	50	50	50	50	0	0	0	0	0
96 hr + Internal Damage Mortality	50	50	50	50	0	0	0	0	0
SHOT 2									
Number Tested	50	50	50	50	50	50	50	50	50
96 hr Mortality	50	50	50	50	0	0	0	0	0
96 hr + Internal Damage Mortality	50	50	50	50	0	0	0	0	0

Table 8.7.- Percent bluegill mortality based on live/dead counts (n=80 at each distance tested) resulting from the explosive demolition of dam piers at Locks and Dam 26 without and with the use of a bubble curtain. (From Keevin et al. (In press))

Distance From Blast		Percent Mortality[1]	
Feet	Meters	Without Bubble Curtain	With Bubble Curtain
65	19.8	100	19
105	32.0	100	6
145	44.2	100	7
185	56.4	100	1
225	68.6	100	3
265	80.8	100	3
305	93.0	78	0
345	105.2	70	3
385	117.4	58	0
Control	---	15	5

[1]Percentages were rounded to the nearest whole number.

Practical considerations should be taken into account when considering the use of a bubble curtain including: location, size and type of the explosive charge; physical water conditions; the quality of the fishery; fish species targeted for protection; and, presence of endangered species and potential number of fish exposed. Placement of a bubble curtain may not be warranted. A benefit/cost analysis should be conducted considering potential for fish mortality and cost of construction, placement and operation of a bubble curtain. Under certain situations, environmental damage may be minimal and it may be more realistic to accept the level of mortality as a societal cost or to mitigate by testing and control, monetary compensation, replacement stocking, or by other means, rather than using a bubble curtain.

McAnuff and Borren (1989) reviewed agency mitigation requirements for underwater blasting in commercial fishing waters at a dock facility near Port Dover, Ontario. A number of practical objections to bubble curtain use were considered to be all but prohibitive including: difficulties involved in supplying compressed air in sufficient quantities to provide a bubble curtain to surround the minimum area required for a viable blast; moving the bubble curtain system to a new location after every blasting operation; and, use during inclement weather. The probable costs of bubble curtain use were considered to be extremely high. It was agreed by Ministry of Natural Resources representatives that bubble curtain use would not be considered mandatory until a fish mortality rate of 50% was attained at fish cages placed at a radius of approximately 800 m from the blasting operation.

Physical Barriers. Physical barriers include any solid barrier that contains or reduces the explosive pressure wave. There is no comprehensive published information on the effectiveness of either full or partial physical barriers in mitigating impacts to aquatic life; however, any solid barriers that prevents or reduces transmission of an explosive pressure wave would probably be effective. Four agencies have recommended physical barriers to reduce the impacts of underwater explosions. In response to a permit request to demolish a bridge using explosives, the Indiana Department of Natural Resources recommended that: "Piers must be enclosed in steel sheeting before any blasting take place".

The Connecticut Department of Environmental Protection placed seasonal permit

restrictions on explosive bridge pier removal including: prohibiting underwater blasting (April 1-July 15), requiring a dewatered cofferdam system (July 16-March 31), and requiring cofferdams that have not been dewatered (November 15-February 28) in order to protect the shortnose sturgeon (Acipenser brevirostrum), a Federally endangered species. Use of the cofferdam was successful in reducing peak pressures below the 100 psi (690 kPa) maximum limit imposed by the National Marine Fisheries Service (Anonymous 1994).

In response to a plan to remove pilings in Pine Island Bayou and the Neches River, the Texas Parks and Wildlife Department recommended that the applicant: "Contain the pressure wave as much as possible. Investigate the use of 'blast blankets' around/upon the explosives to minimize and contain the pressure waves..."

MITIGATION RECOMMENDATIONS

Evaluation of project impacts and development of effective mitigation strategies requires three components: 1. a working knowledge of explosives and explosives engineering; 2. a thorough understanding of the environmental effects of underwater explosions; and, 3. information on current mitigation techniques related to explosives, well grounded in practice and theory. Rarely does the natural resource agency have personnel experienced in explosives engineering and it is equally unlikely that a blasting company would have biological expertise. It is even more unlikely that either group would have information on mitigation techniques. In addition, it is difficult to quickly obtain information concerning the environmental effects of underwater explosives use and mitigative measures. The majority of literature on these subjects is in obscure publications (corporate and government reports, symposium proceedings, and obscure international journals).

The blaster will probably have to work more closely with natural resource agencies to reduce potential impacts. The alternative to working in a cooperative manner with the permitting agency(ies) may be not to work at all. The following recommendations would foster communication between the natural resource agency and the blaster. The key to better communications is information acquisition and exchange between both parties.

1. Provide the regulatory agencies a detailed blasting plan.
2. Schedule meeting between the regulatory agency and blaster. If there are concerns during review of detailed blast plan, require a meeting to review the proposal. Work cooperatively to reduce impacts.

Keevin and Hempen (1995) developed a three tiered mitigation planning process that requires a cooperative spirit between the blaster and natural resource agencies. This approach relies heavily on the exchange of information outlined above.

Based on the preceding review of mitigation techniques, the following measures are recommended to reduce the adverse effects of underwater explosive use.

Blast Design Parameter.

1. Evaluate the need to use explosives. If practical alternatives are available and not excessively expensive, require their use.
2. Plan the blasting program to minimize the total weight of explosive charges per shot and the number of shots for the project.
3. Use angular stemming material of sufficient length in drill holes to reduce energy dispersal to the aquatic environment.
4. Subdivide the charge, using detonating caps with delays or delay connectors with detonating cord, to reduce total pressure. Avoid the use of submerged

detonation cord.

5. Use decking when possible in lengthy drill holes to reduce total pressure.
6. For seismic exploration use non-explosive sources when possible or use linear charges for open water shots or buried charges.
7. Use shaped charges to focus the blast energy when submerged surface charges are necessary, reducing energy released to the aquatic environment during demolition.

Biological Parameters

1. Evaluate the quality of the fishery resource, based on existing information. If there have been no previous surveys of the blast area, and there is reason for environmental concern, require or conduct a survey. Based on the quality of fishery resources, make a decision concerning the magnitude of potential impacts.
2. Require or conduct mathematical mortality modeling to determine potential fishery impacts. Based on predicted impacts, make rational decisions concerning compensation or use of other mitigation techniques.
3. If applicable, limit season of explosive use to avoid major migration periods, spawning seasons, spawning beds, or larval drift.
4. If there is a concern with migrating fish, use sampling techniques (e.g., hydroacoustics) to avoid impacting large congregations.
5. Use non-explosive noise techniques to move fish from the immediate blast zone.
6. Require the presence of an agency observer, with authority to halt blasting or require use of mitigation techniques, if mortality is excessive based on pre-determined mortality levels.
7. If mortality is excessive, based on pre-determined mortality levels or observation, require significant blasting revisions (that allow the work to proceed but lowers mortality), or compensation.
8. If fish mortality is excessive, based on observation or mathematical modeling, or if species of special concern are present (e.g., endangered species), require the use of properly designed bubble curtains or physical barriers.

A TIERED MITIGATION PLANNING PROCESS

Keevin and Hempen (1995) developed a tiered mitigation approach based on: 1) the blasting design; 2) biological criteria; and, 3) use of physical mitigation features. Each tier requires progressively more mitigation measures to avoid impacts to aquatic resources. The tiered mitigation planning process will require a cooperative spirit between the blaster and natural resource agencies.

TIER I MITIGATION PLANNING

Tier 1 planning involves the development of a blasting design by the explosive engineer which attempts to reduce or limit the amount of explosives being utilized. It also involves an assessment of potential environmental effects, based on the existing aquatic resources in the blast area (this may involve survey work) and mathematical mortality modeling by natural resource personnel. An initial coordinated effort is required between the blaster and the natural resource agency.

Blast Design Parameters

1. Evaluate the need to use explosives. If practical alternatives are available, use non-explosive techniques.
2. Plan the blasting program to minimize the weight of explosive charges per delay and the number of days of explosive exposure.

Biological Parameters

1. Evaluate the quality of the fishery resource, based on existing information. If there have been no previous resource surveys of the blast area and there is reason for environmental concern, require or conduct the survey. Based on quality of fishery resources, make a decision concerning magnitude of potential impacts.
2. Conduct mathematical mortality modeling to determine potential fishery impacts (Hempen and Keevin 1995). Based on predicted impacts, make rational decision concerning compensation or use of other mitigation techniques.

TIER II MITIGATION PLANNING

Should the development of an explosive design and environmental assessment of potential impacts result in a determination that "important" aquatic resources are risk, then Tier II planning should be implemented. Tier II blast design mitigation measures involve the use of delays, stemming, decking, et cetera to reduce water borne shock waves entering the aquatic environment. Many of these types of features would be part of good explosives design to reduce peak overpressure or ground vibration. Biological parameters include such measures as seasonal blasting limits to avoid spawning fish, large migrations, or periods of larval drift.

Blast Design Parameters

1. Use adequate lengths of angular stemming material in drill holes to reduce energy dispersal to the aquatic environment.
2. Subdivide the explosives deployment using delays to reduce total pressure. Carefully consider detonating cord in the firing system, as greater mortality could result.
3. When possible use decking in drill holes to reduce total pressure.
4. For seismic exploration require non-explosive sources when possible. If this is not possible use linear charges for open water shots or buried charges.
5. Use shaped charges for surficial charges to focus the blast energy, reducing energy released to the aquatic environment during demolition.

Biological Parameters

1. Recommend presence of an agency observer with authority to resolve revised blast parameters or to halt blasting or to require use of mitigation techniques, if mortality is excessive based on pre-determined mortality levels.
2. If applicable, limit season of explosive use to avoid major migration periods, spawning seasons, spawning beds, or larval drift.
3. If there is a concern with migrating fish, use sampling techniques (e.g. hydroacoustics) to avoid impacting large congregations.
4. Use non-explosive scare techniques to move fish from the immediate blast zone.

TIER III MITIGATION PLANNING

Should there still be environmental concerns after Tier I and II planning efforts, Tier III measures can be employed. If important commercial or sport species are being impacted, there is always the option of monetary compensation for fish losses based on replacement values developed by the American Fisheries Society (1992, 1993). Threatened and endangered species can present special problems with regulatory permitting requirements. Bubble curtains or other physical barriers can be used to avoid mortality of these species (Hempen 1993).

1. If mortality is excessive, based on pre-determined mortality levels or observation, state or federal fish and wildlife agencies can require compensation.
2. If fish mortality is excessive, based on observation or mathematical modeling, or if species of special concern are present (e.g. endangered species) require the use of bubble curtains or other barriers.